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Flexural properties as a basis for strength grading of dry round bamboo

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September 2016

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Abstract

This thesis presents the results from 286 four-point bending tests carried out on dry Guadua angustifolia Kunth culms for which a number of mechanical and physical properties were measured and documented. The aim of this thesis is to demonstrate that relationships can be established between destructively and non-destructively measured properties and based on these relationships, to evidence that a grading system for bamboo is possible. The significance of this is that graded bamboo would enable designers to use the material safely and economically in construction.

Correlations between flexural strength ($f_{m,0}$), static modulus of elasticity ($E_{m,s}$), dynamic modulus of elasticity from stress-waves (E_d) and density (ρ) provided mediocre results with R^2 ranging from 0.34 to 0.56. However, properties such as flexural stiffness ($EI_{m,s}$), flexural capacity (M_{max}) and mass per unit length (q_{test}) which are less dependent on geometric properties, provided much stronger correlations with R^2 ranging from 0.85 to 0.94. Based on these findings, it is suggested that instead of using a stress-based approach for bamboo design, we should employ a capacity-based approach as is often used with engineered timber products.

The analysis showed that mass per unit length, average external diameter and flexural stiffness were well correlated with flexural capacity and it is therefore proposed that these parameters could be used as Indicating Properties (IPs), either separately or in combination, for flexural capacity in a grading procedure for dry full-culm bamboo as presented at the end of this thesis.

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List of notations

$f_{m,0}$ flexural or bending strength, (modulus of rupture)

f_v shear strength

$E_{m,s}$ static modulus of elasticity, established from static bending tests

E_d dynamic modulus of elasticity, established from a dynamic stress wave technique

E_p modulus of elasticity, established from point-load deflection test

ρ density calculated as mass per volume

EI_d flexural stiffness, established from dynamic stress wave technique

$EI_{m,s}$ flexural stiffness, established from static bending tests

EI_p flexural stiffness, established from point-load deflection test

q_{test} mass per unit length

M_{max} Maximum bending moment or flexural capacity, established from static bending tests

D_{mean} average external diameter of the culm

t_{mean} average wall thickness of the culm

f_l fundamental frequency, measured from dynamic stress wave technique

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1 Introduction

Design codes and standards provide guidance based on the mechanical properties of a structural material however due to their inherent variability, the determination of mechanical properties for natural materials such as timber or bamboo is not as simple as for manufactured materials such as precast concrete or steel where quality and strength can be prescribed during the manufacturing process. In timber engineering, a process referred to as strength grading is currently used; this involves non-destructively testing every member and assigning it to a grade which gives the designer information about the strength of each specific piece. At present, bamboo design codes and standards only briefly refer to grading as a means of determining the mechanical properties of the material (Trujillo 2013); designers are therefore unable to use bamboo with confidence and this potentially limits the wider use of bamboo as a structural material.

Early research into bamboo as a construction material was carried out by Janssen in 1981 and the first standard to be published was 'IS:6874 – Methods of tests for round bamboos' which was introduced by the Bureau of Indian Standards in 1973 (BIS 1973). Following this, there was little further advancement until the publication of bamboo design codes from Colombia in 2002 and 2010 (Trujillo, Ramage and Chang 2013) and Section 3B of the National Building Code of India in 2004 (BIS 2004). The first international standard for bamboo was published by the International Standards Organisation (ISO 2004a, 2004b and 2004c) in 2004 (Trujillo and López 2016). Design codes also emerged in Ecuador, Peru and The Philippines and whilst some reference is made to the determination of strength properties, there has been little guidance and no formal grading procedure has been presented to date.

1.1 Project aims and objectives

The primary aim of this investigation is to establish whether or not grading of full-culm round bamboo is possible and if it is, to propose a grading method which could be adopted in order to safely estimate the mechanical properties of bamboo from non-destructively measurable properties. This will be dependent on the following aims and objectives being successfully fulfilled:

1. Investigating the use of dynamic methods of establishing modulus of elasticity;
2. Investigating the implementation of a simple deflection test to estimate flexural stiffness;
3. Investigating the influence of the geometric uncertainty of bamboo culms on the determination of mechanical properties;
4. Demonstrating that relationships can be established between destructively and non-destructively measurable properties;
5. Establishing potential Indicating Properties (IPs) from which mechanical properties can be estimated in the proposed grading procedure.

1.2 Scope of the project

There are a number of limitations to the scope of this investigation due to time constraints and the availability of equipment and materials for testing. The project is therefore limited as follows:

1. Only one species of bamboo, Guadua angustifolia Kunth (Guadua a.k.) was procured and available for testing;
2. All bamboo is tested in a dry condition (below 20% moisture content) as it was not possible to procure any green bamboo;
3. The minimum length of specimens tested in this investigation was restricted to 3300 mm to comply with the requirements of the static bending test;
4. Only flexural properties were investigated as it was not possible to test specimens for shear and compressive strength in the time available.

2 Literature review

2.1 Anatomy of bamboo

As explained by Liese (1998), bamboo plants exhibit rapid growth, increasing in height but not diameter as they grow. They are composed of nodes and hollow internodes with branches growing from the nodes. The walls of bamboo culms are composed of material containing vascular bundles held within a matrix and it is the vascular bundles (the fibres) which give the culm its notable strength (Liese 1998).

The case for using full-culm round bamboo for structural applications has been justified to a great extent by the work of Amada et al (1996) and (1997) who argued that bamboo is extremely well evolved to resist environmental loading due to its geometry and the unique composition of the wall material. This research was significant because both geometric and material properties were considered together and a combination of these properties are central to the grading system proposed later on in this thesis.

Even though Amada et al (1996) and (1997) only considered wind loading, the findings of their research are key to understanding why bamboo is such an efficient material. They found that at the macroscopic scale, diameter and wall thickness decreased almost linearly with increasing height whereas internode length peaked at mid-height. Due to this decreasing diameter and wall thickness with height, the applied moment due to wind loading results in a fairly constant maximum applied stress, making bamboo very efficiently designed to withstand environmental loading.

Analysis of the microscopic structure in Amada et al (1996) and (1997) showed that the number of vascular bundle sheaths within the matrix increased from the inner layer to the surface and increased with increasing height along the culm. The vascular bundles were also found to be almost twice as dense as the matrix surrounding them. They noted that the microscopic structure of bamboo resembles a "functionally graded material"; which is also true at the macroscopic scale as discussed.

Bamboo as a functionally graded material has also been reported in various other studies such as Ghavami, Rodrigues and Paciornik (2003) who also investigated the variation in the distribution of fibres within the matrix based on the assumption that bamboo can be considered as a composite material. Amada et al (1996) and (1997) also found that the random orientation of fibres around the nodes (compared with unidirectional fibre orientation in the internodes) provided “isotropic properties” thereby creating additional reinforcement for the plant.

In Amada et al (1996), tensile tests on small strips from different positions along the culm showed increasing axial tensile strength from the inner layer to the surface; the tensile strength of the vascular bundles was around twelve times greater than the matrix. Modulus of elasticity similarly increased from the inner layer to the surface; the analysis showed that modulus of elasticity at the surface was twenty-three times greater than at the inner layer. This suggests that the vascular bundles provide bamboo’s strength and stiffness; in particular, the increasing density of vascular bundles towards the surface makes the plant well designed to withstand the bending stress resulting from wind loading. Furthermore, because the vascular bundles are more densely packed with increasing height, they counteract the loss of strength and stiffness due to decreasing diameter and wall thickness. However due to the orientation of the vascular bundles, they do not contribute significantly to the compressive strength of bamboo with circumferential strength found to be less than half of the axial tensile strength of the matrix.

2.2 Mechanical properties of bamboo

The mechanical properties of bamboo were first considered in the early 1900s (Meyer and Ekelund 1923) and significant work in this area came from Janssen (1981) and (1991). Over the years, density has been identified as a good indicator of strength in bending, compression and tension by many researchers (Ota 1950, Sekhar Rawat and Bhartari 1962, and Zhou 1981), and most notably by Janssen (1981). This corroborates the observation discussed in Section 2.1 that the vascular bundles provide bamboo with its strength and the more densely packed the fibres are, the stronger the bamboo.

The mechanical properties of bamboo with respect to the age of the plant and the position along the culm of Guadua a.k. bamboo were presented by Correal and Arbeláez (2010) who used the procedures contained in ISO 22157-1 (ISO 2004b) for bending, compression and shear parallel to the grain to test samples of various ages and positions. Their investigation found that the top portion of the culm, referred to in this thesis as 'superior', exhibited the highest strength and modulus of elasticity in bending, compression and shear; which they attribute to the increasing density towards the tip of the culm. This is corroborated by Amada et al (1996) and (1997) who noted that fibres were more densely packed with increasing height.

Another observation from Correal and Arbeláez (2010) was that Guadua a.k. reached its peak maturity between three and four years of age based on the finding that modulus of elasticity, strength and density peaked at this age. This is supported by Liese and Weiner (1996) who stated that bamboo reached maturity between two and three years. The effect of age has widely been accepted as a property which influences the strength of bamboo in studies including Abd Latif et al (1990), Sattar, Kabir and Bhattacharjee (1990) and Norul Hisham et al (2006).

With regard to modulus of elasticity however, Correal and Arbeláez (2010) observed that modulus of elasticity in bending and compression was independent of age or position along the culm for bamboos aged between three and five years, specifically in the elastic zone. For the purposes of formulating a grading procedure, it was therefore felt that it is important to consider a range of ages in this thesis (as documented in Table 2) because in practice it is likely that the age of culms may not be known with much certainty.

Another important study with particular relevance to this thesis was conducted by Gnanaharan, Janssen and Arce (1994) who considered various test methods for determining the flexural properties of Guadua a.k. The investigation concluded that there were substantial differences in the modulus of elasticity and strength values determined from the different tests which included four-point bending of longer specimens and three-point bending of short specimens and split specimens. Short specimens tested in three-point bending did not exhibit pure bending behaviour and the results were less useful however Gnanaharan, Janssen and Arce (1994) proposed that on the basis of their four-point bending test, it is possible to predict modulus of elasticity and bending strength from density or diameter for which they established strong correlations. This assertion forms the basis of this investigation into grading because the ability to successfully grade bamboo relies on the potential for using non-destructively measurable properties as indicators of strength.

As prescribed in ISO 22157-1 (ISO 2004b) and employed in this investigation, Gnanaharan, Janssen and Arce (1994) recommended a four-point bending test instead of three-point bending to ensure a constant moment zone without transverse loading which could induce shear failures. Vaessen and Janssen (1997) also investigated the minimum length of specimens required in four-point bending tests to ensure an adequate free span and avoid shear failures being initiated as is common with short spans; seven tests were carried out and compared against a theoretical model for which an equation is presented and it was concluded that an optimum free span based on the geometry of a specimen does exist. Gnanaharan, Janssen and Arce (1994) also applied loading through saddles to minimise the risk of crushing and the initiation of shear cracks. Gnanaharan, Janssen and Arce (1994) presented the results of twelve bending tests and whilst their observations provide an important starting point, this investigation aims to establish a much larger data set from which correlations can be found with greater reliability.

2.3 Dynamic testing of bamboo

An important advancement in the prediction of the mechanical properties of bamboo from non-destructive methods was made by Lin, Tsai and Wang (2006) who investigated the bending strength and dynamic modulus of elasticity of Moso bamboo laminae using ultra-sonic wave velocity. Lin, Tsai and Wang (2006) did not consider full-culm bamboo however their research is relevant to grading for round bamboo because it similarly relies on the use of dynamic methods to establish mechanical properties.

Using a portable Pundit meter, density and ultrasonic-wave velocity were recorded and the dynamic modulus of elasticity was calculated. Modulus of elasticity and bending strength were established from static bending tests with mid-span loading. They found that dynamic modulus of elasticity was a good predictor of modulus of elasticity from bending with an R^2 value of 0.75; they therefore concluded that non-destructive testing can be successfully used to predict the mechanical properties of Moso bamboo. However, bending strength did not correlate well with dynamic modulus of elasticity with an R^2 value of 0.58 compared with 0.68 against modulus of elasticity in bending.

2.4 Current design codes for bamboo

'IS:6874 – Methods of tests for round bamboos' published by the Bureau of Indian Standards in 1973 (BIS 1973) was the first formal bamboo standard to be issued and provides guidance on testing full-culm round bamboo. Following his research in 1981, Janssen led an initiative through the International Network for Bamboo and Rattan (INBAR), with the aim of developing an international standard for bamboo design. Following over a decade of work, the initiative published an international standard in 2004 through the International Standards Organisation (ISO).

This included 'ISO 22157-1: Bamboo – Determination of physical and mechanical properties – Part 1: requirements' (ISO 2004b), 'ISO 22157-2: Bamboo – Determination of physical and mechanical properties – Part 2: laboratory manual' (ISO 2004c) and 'ISO 22156: Bamboo – Structural design' (ISO 2004a). ISO 22157-1 (ISO 2004b) contains the following test procedures: moisture content, mass by volume (i.e. density), shrinkage, compression parallel to fibres, bending, shear and tension parallel to fibres. ISO 22157-2 (ISO 2004c) explains how to use these standards and provides guidance on experimental test procedures. ISO 22156 (ISO 2004a) presents a design philosophy for bamboo and some basic guidance for structural design, however there is very little practical guidance which would be required by designers and would be expected in a design code. It does, however, contain guidance with regards to the derivation of characteristic and allowable stresses.

ISO 22157-1 (ISO 2004b) has been recognised across the world where the standard has either been adopted either directly or with some adaptations. These countries include Colombia, Ecuador, Peru, Jamaica, Ethiopia and India. The prescribed test procedures contained within the ISO standards have enabled bamboo researchers in these countries to ensure that test results can be compared with confidence and have provided a basic outline from which we can advance towards further standardisation. However, there are limitations to the ISO standards and how useful they are in practice.

Firstly, and arguably one of the main deficiencies of ISO 22157-1 (ISO 2004b) is that it does not contain any reference to tests for determining tensile strength perpendicular to the direction of the fibre which is arguably one of the most important mechanical properties of bamboo.

ISO 22157-1 (ISO 2004b) contains guidance on conducting shear tests using the 'bow-tie' procedure however the first limitation of this, as noted by Janssen (1981), is that shear strengths derived from the bow-tie test are typically larger than those obtained from shear failures in flexural tests and this arguably limits the usefulness of this test. As discussed later on in this thesis, it has been observed that shear failures are a commonly observed failure mode in bamboo bending tests.

It should be noted that the bow-tie test results in pure mode II shear failures whereas bending tests introduce a component of mode I behaviour whose interaction naturally 'weakens' the mode II capacity (Richard 2013).

The bending test detailed within ISO 22157-1 (ISO 2004b) has been used as the basis for the experimental programme employed in this thesis, however as noted later on, ISO recommends the use of wooden saddles through which the load is applied but they have the risk of inducing crushing failures and the test therefore needs to be modified to include fabric straps. Furthermore, the ISO guidance neglects to take account of any local deformations at the supports through the use of LVDTs for example and this has therefore been addressed in this thesis.

2.5 Standardisation of bamboo design codes

Standardisation of the design and construction processes for bamboo is important if it is to be widely accepted as a building material; this is particularly important for test procedures so that data collected around the world for different species can be used in the creation of universal design codes as discussed in Harries, Sharma and Richard (2012). The ISO standards (ISO 2004a, 2004b and 2004c) do attempt to provide standardisation however as noted by Harries, Sharma and Richard (2012), the limit state approach proposed in the standards is problematic in practice because of the limited specialist knowledge and prevalence of traditional building methods which often rely on experience alone.

The ISO standard (ISO 2004b) includes test procedures for full-culm compression, longitudinal tension, longitudinal shear and full-culm bending. As pointed out by Harries, Sharma and Richard (2012), the full-culm bending test which this investigation is based on is susceptible to shear failures and the resultant bending strength is therefore not accurate; the standard does not address longitudinal shear which is an important failure mode in bamboo.

This investigation also requires the determination of moisture content which is discussed in Section 5.2; the procedure prescribed in ISO 22157-1 (ISO 2004b) has not been employed due to the impracticality of the method. Harries, Sharma and Richard (2012) also point out the necessity of tests to be simple enough to be carried out in the field by non-technical personnel who may not have access to laboratory equipment; this has therefore been a primary consideration of the grading procedure proposed in this thesis.

2.6 Gaps in knowledge

To date, experimental results have been published in various studies which provide a basic understanding of the mechanical behaviour of bamboo. Some design codes such as Colombia's NSR-10 provide some information on the strength and stiffness of specific species whilst ISO 22156 (ISO 2004a) provides guidance on the derivation of mechanical properties, although the practical use of these standards is limited. As noted by Trujillo (2013), some guidance on visual grading of bamboo does exist however there is a lack of robust experimental evidence to support it and there is almost no reference to the characterisation of different species.

This study therefore attempts to provide a more comprehensive analysis which considers the flexural properties of one species, Guadua a.k., and uses experimental data to formulate a grading procedure which could be incorporated into a formal design code for use in practical applications.

3 Investigation into the energy and carbon impact of bamboo on the environment

Bamboo has been widely recognised as a sustainable construction material as it is a fast growing and renewable resource which can be procured at a low cost. As detailed by Kuehl and Yiping (2012), bamboo has the potential to counteract climate change through carbon off-setting. A study by Van der Lugt, Dobbelsteen and Abrahams (2003) investigated the environmental impact of both full-culm and engineered bamboo and compared their findings with traditional construction materials. A lifecycle assessment was conducted and it was concluded that full-culm bamboo outperforms materials such as concrete, steel and wood by a factor of up to twenty; this was not the case for engineered bamboo and therefore supports the case for developing a grading method for full-culm bamboo so that its environmental benefits can be taken advantage of.

To investigate the environmental impact of the bamboo used in this investigation, a lifecycle assessment of the specimens has been conducted. The assumptions used to calculate the energy and carbon impact for one shipment of bamboo containing 450 culms of 6m length per 20 foot shipping container transported from Colombia to the UK are detailed in Appendix A.

Following harvesting of the bamboo culms, they are transported from the plantation in a medium-sized diesel lorry to the drying facility located approximately 20 km away from the plantation; three trips are required to transport the 450 culms of 6m length to the drying facility. At the drying facility, the culms are first treated in a 12% boron solution which requires water in a tank to be heated to 60˚C; 500 linear metres of bamboo are passed through this tank over a period of approximately 8 hours. The total treatment time required per shipment is therefore calculated to be 43.2 hours.

A carbon-neutral solar oven is then used to reduce the moisture content of the culms from 50-60% to 30-40% before drying in a kiln. The kiln requires approximately 0.2 m^3 of plant-based charcoal and ten 15 m lengths of waste bamboo per hour to fuel it. Based on the information provided by the supplier, the drying process take roughly 36 hours with an output of 500 linear metres of bamboo. The total kiln drying time required for the shipment is therefore calculated to be 194.4 hours requiring a total of 39 kg of charcoal and 405 kg of recycled waste bamboo.

The dried and treated bamboo is then transported approximately 200 km from the drying facility to the shipping port in an articulated diesel lorry. The culms are shipped in a standard 20 foot container carrying 450 poles of 6m length each for a total shipping distance from Colombia to the UK of 8,600 km.

The energy consumption and CO_2 emissions associated with each step of the process are summarised in Table 1 together with the embodied energy and embodied carbon of the shipment. The energy and carbon intensity of each step is illustrated in Figures 1 and 2.

Table 1: Energy consumption and CO_2 emissions for each process step

Process Step	**Distance (km)**	**Input**	**Energy consumpti-on (kJ)**	**Embodied energy (kJ/kg)**	**CO_2 emissions (kg)**	**Embodied carbon (kg CO_2/kg)**
Cultivation and harvesting	-	Water and sunlight*	0	0	0	0
Sawing culms and branch removal	-	Carried out by hand*	0	0	0	0
Quality control	-	Visual inspection*	0	0	0	0
Transport from plantation to drying facility	60	Diesel	191760	26.3	17.3	0.002371
Solar oven	-	Sunlight*	0	0	0	0
Drying in kiln	-	Charcoal and waste bamboo	8875980	1217.6	190.8	0.026176
Treatment with boron solution	-	12% boron solution and heat	907200	124.4	27.6	0.003781
Transport from drying facility to shipping port	200	Diesel	2400400	329.3	216.4	0.029681
Shipping	8600	Diesel	23196780	3182.0	1098.2	0.150647
TOTAL	8860		35572120	4879.6	1550.3	0.212657

* Carbon neutral

Figure 1: Energy consumption per process step

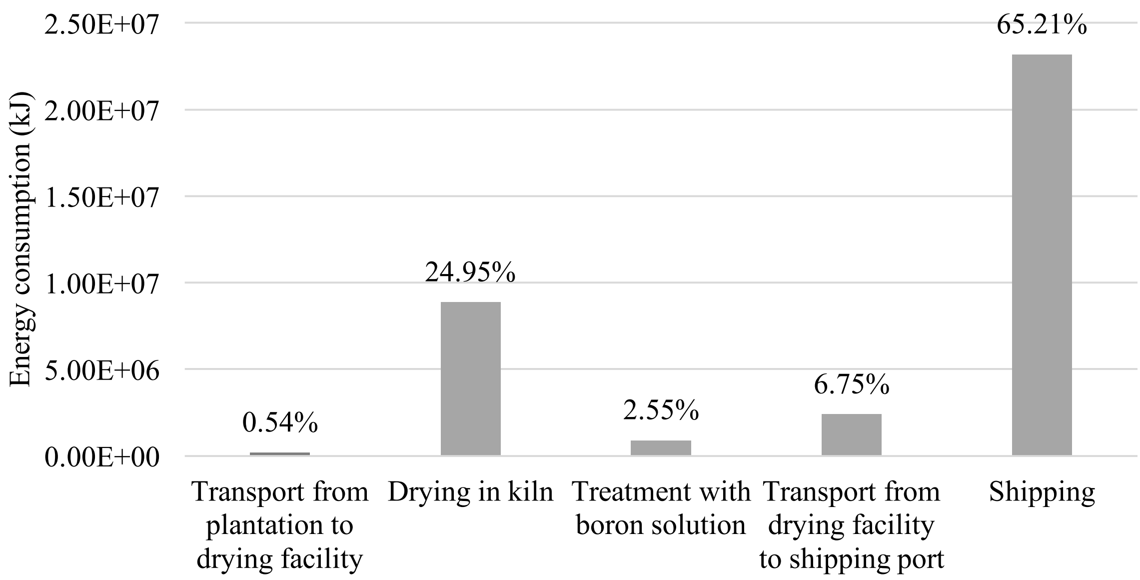
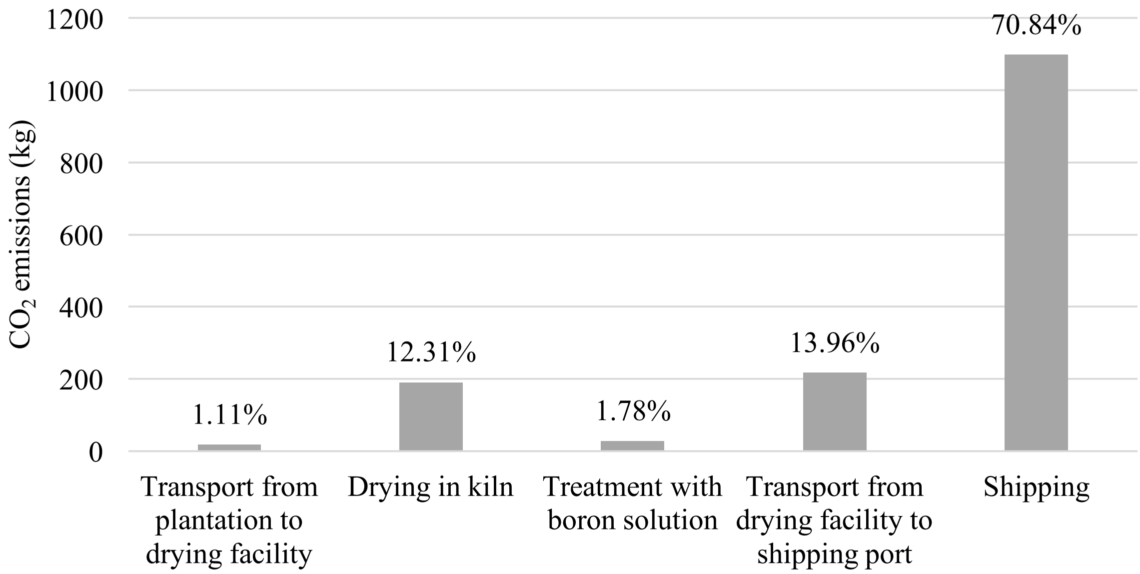


Figure 2: Carbon dioxide emissions per process step



4 Strength grading in timber

As previously discussed, design codes and standards are based on an understanding of the mechanical properties of the material and it is therefore important that these mechanical properties can be relied upon with confidence. This is less of an issue for manufactured materials where the manufacturing process and quality of the supply can be controlled. For natural materials such as timber and bamboo, it is impossible to avoid variability in the quality of the material and thus every piece will have unique physical and mechanical properties. This however, should not hinder the use of natural materials and in timber engineering, the process of strength grading is employed whereby every piece supplied to the market is tested and then sorted into structural grades on the basis of its inferred strength (Benham, Holland and Enjily 2003); this enables the designer to predict its design capacity with adequate confidence.

There are two types of strength grading; visual or machine grading, each of which are discussed in further detail in the following sections.

4.1 Visual grading

Visual grading of timber is a manual process whereby each piece is inspected by trained and experienced personnel and the physical characteristics of the piece (such as the size and position of knots) are observed and measured. Requiring no instrumentation or test equipment, it is the least capital intensive way to grade timber, however it is both time and labour intensive. This method of grading relies solely on the inspection of visual characteristics and is prone to human error so it has to be much more conservative than machine grading therefore leading to an inefficient use of the material (Johansson 2003).

Modifications to the visual grading process mean that although it is a manual process, it can be machine assisted and its key benefit is that it can be verified after grading; this is not possible with machine grading as will be discussed in Section 4.2.

The application of visual grading in bamboo was explored by Janssen (1981) who noted that "compared with wood, bamboo seems to be more regular: problems as to knots or slope of grain do not occur".

4.2 Machine grading

Machine strength grading is used to infer the mechanical properties of timber (e.g. stiffness and strength) by carrying out non-destructive testing on each piece. The process relies on the relationship between non-destructively measured properties, widely referred to as Indicating Properties (IPs), to one or more grade determining properties. For example, modulus of elasticity in bending ($E_{m,s}$) is often used as an IP to infer bending strength ($f_{m,0}$) which is the grade determining property; the process of inferring the grade determining property from the IP often employs the use of x-rays, ultrasonic waves, measurement of density or hardness, and sometimes, a combination of these. The resultant grade determining property is then used to categorise the piece of timber into a 'strength class' which has several associated physical and mechanical properties (Benham, Holland and Enjily 2003).

The process is much faster and more accurate than visual grading, does not need to be as conservative, and is less prone to human error. However, the disadvantage is that the process cannot be verified after grading has been carried out and it does still require human input to provide a visual override for the presence of any defects (Ridley-Ellis, Stapel and Baño 2016).

Machine grading can either be based on the 'output control' method or the 'machine control' method for calibration of the grading equipment to reliably infer the grade determining property from one or more of the IPs.

In the machine control method, the grading machine is calibrated on the basis of hundreds (often thousands) of destructive tests on a given species from a specific plantation to correlate the IPs with the grade determining properties. The calibration settings of the grading machine must be approved by the relevant body (CEN/TC24 in Europe) to ensure that the process is safe. Undertaking the large number of initial destructive tests is an expensive process and it is necessary that these destructive tests are repeated periodically to ensure the validity of the observed correlations between IPs and grade determining properties. Furthermore, the grading machines must be subject to strict inspection and control processes, however once the machine control method has been established, it is reasonably simple to run.

The output control method does not require as many destructive tests to be carried out as the machine control method however the destructive tests must be repeated much more regularly and the operational costs of this method are therefore higher. Based on the results of the destructive tests, the calibration of the grading machine is constantly adapted to optimise yield (Ridley-Ellis, Stapel and Baño 2016) through a process known as the Cumulative Sum method or CUSUM which involves proof-loading a sample to confirm that the strength of the specimens is within acceptable limits (Sandomeer and Köhler 2007).

In Europe at least 900 destructive bending tests are required to establish the grading machine settings and calibration under BS EN 14081-2 (British Standards Institution 2010a). Third party verification is a requirement for strength grading to ensure quality control of the grading process and to provide confidence in the timber supply chain. The calibration of grading machines is based on the specific sample of timber which will be graded, based on the mean timber quality. The grade determining properties are based on characteristic properties from BS EN 338-1-1 (British Standards Institution 2010b) including characteristic (5^{th} percentile) bending strength, mean modulus of elasticity and characteristic (5^{th} percentile) density.

Due to the statistical nature of the process whereby calibration of the machine is based on the correlations observed in the initial test data, some pieces will be rejected. Pieces that are accepted will be assigned a specific strength property (Benham, Holland and Enjily 2003). Also because it is a statistical process, it is impossible to know the actual strength of any specific piece of graded timber in the batch; it is only possible to say that there is a high probability that the graded piece has the strength specified to it as a result of it being subjected to the grading process (Ridley-Ellis, Stapel and Baño 2016).

4.3 Grading of bamboo

Grading is valuable because it reduces the variability of the supply and gives designers confidence in the structural capacity of a given specimen. This means that structures can be designed with more confidence, with lower safety factors required and more economical and efficient construction. Machine grading does involve high capital and operational costs, especially in comparison with visual grading, however it enables the safe use of a naturally variable material and makes it available to the commercial market with relatively low values for the partial material factors (γ_M) used for timber in Eurocode 5 (British Standards Institution 2010c).

If bamboo is to become a commercially viable material which designers can specify with confidence, the bamboo supply chain must be made more reliable in the way that the timber supply chain is with the use of strength grading. At present, there is very little quality control in bamboo supply as material selection and construction is largely based on experience instead of certification.

5 Experimental programme

In this investigation, two separate batches of Guadua a. k. bamboo have been tested to determine the actual and predicted bending properties of bamboo. The first batch of specimens of Guadua a.k. tested in this investigation were harvested from the municipality of Caicedonia in Colombia and the second batch from the Quindío province in Colombia. Specimens were shipped to the UK from Colombia and transported to our laboratory for testing.

With the aim of deriving correlations between the destructively and non-destructively measurable properties of bamboo, non-destructive testing based on stress-wave velocity is used to determine the dynamic modulus of elasticity (E_d) and a destructive four-point bending test is subsequently carried out to determine the static modulus of elasticity (E_s), bending moment capacity (M_{max}) and bending strength ($f_{m,0}$) of each specimen. A simple point-load deflection test is also carried out to determine whether modulus of elasticity calculated from the deflection resulting from the application of a lump mass (E_p) can provide a reliable approximation of the static modulus of elasticity from four-point bending.

Bamboo plants can grow to around 30 m high however only the bottom 12 m of the plant is considered useful for structural applications. From this 12 m, at the location of harvesting, the culm was divided into three sections of roughly 4 m length each and specimens were categorised so that their position could be distinguished; the section closest to the root of the plant is referred to as 'inferior', the upper most section is referred to as 'superior' and the middle section is simply referred to as 'middle'. Every specimen of Guadua a.k. was marked with a unique reference according to this position and the age of the sample when harvested. The range of ages and positions along the culm used in this investigation are presented in Table 2. This information has been included as it has been noted that age and position do have some effect on the behaviour of bamboo (Trujillo and López 2016).

Unfortunately, due to difficulties with the supplier, it was not possible to collect information on age and position along the culm for the second batch of specimens harvested from the Quindío province in Colombia and these have therefore been included in Table 2 as 'unknown'.

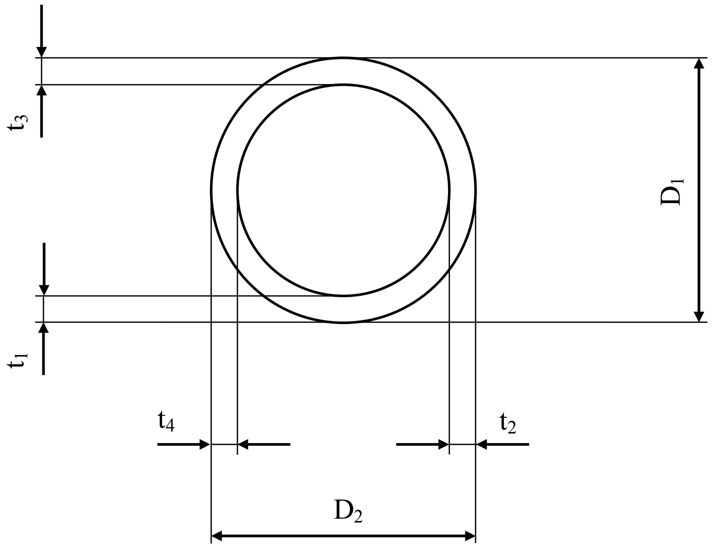
Table 2: Composition of sample, identifying range of positions along the culm and age at harvesting

	Age at harvesting Number of specimens shipped (number of specimens tested)						
Position along the culm	< 2 yrs	2 - 3 yrs	3 - 4 yrs	4 - 5 yrs	> 5 yrs	Unknown	
Inferior - I	19	15	14	15	15		
Middle - M	12	15	15	14	17		
Superior - S	18	18	17	14	19		
Unknown						49	
TOTAL							286

The length of the specimens used in this investigation range from 3708 mm to 5450 mm; the minimum allowable length of the specimens was restricted by the configuration of the supports used in the four-point bending test (see Figure 8) which provided a fixed free span of 3300 mm; this requirement was necessary due to the susceptibility of shear failures being triggered in spans shorter than this. It was not possible to test any specimens longer than 5450 mm due to storage restrictions in the laboratory at Coventry University.

For each specimen, the total length (mm) and mass (kg) are recorded; length is measured with a standard tape measure accurate to the nearest 1 mm and mass is measured using an electronic scale accurate to 0.01 kg. Measurements of diameter (mm) and wall thickness (mm) are obtained with a digital calliper accurate to the nearest 0.01 mm; at both ends of the specimen, diameter is measured at two points perpendicular to one another and wall thickness is measured at four points or for each quadrant of the section as shown in Figure 3.

Figure 3: Measurement of external diameter and wall thickness



The specimens were stored and tested in the Structures Laboratory of the Sir John Laing building at Coventry University, with a mean temperature of 17˚C and relative humidity of approximately 42% over the course of the testing period. Due to logistical difficulties and restrictions in the space available, it was not possible to store them in a conditioning room at a fixed temperature and relative humidity. The laboratory environment was monitored throughout the testing period and a summary is provided in Table 3. The consistency in the range of moisture content readings obtained for each specimen (see Figure 6) demonstrate that the environmental stability of the laboratory was adequate for the purposes of this investigation.

Table 3: Laboratory conditions during testing period

	Temperature (˚C)	Relative Humidity (%)
Mean	17	42
Minimum	13	39
Maximum	18	58

Table 4 contains a summary of all the information recorded in this investigation for each specimen tested. The apparatus used to measure each property has been detailed together with the associated units and precision of the measurement; further explanation is included in the following sections where each experimental process is described. The data recorded as per Table 4 for each specimen is later used to determine the geometrical, physical and mechanical properties of interest.

Table 4: Summary of data recorded for each specimen

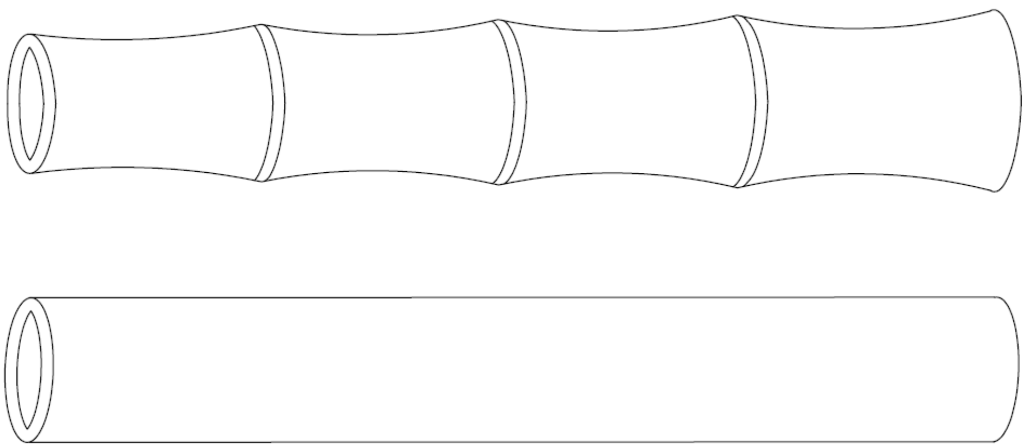
Property recorded		Units	Precision
Prior to four-point bending test			
External diameter	Orthogonal readings at both ends (i.e. four readings) using digital callipers (refer to **Figure 3**)	mm	0.01 mm
Wall thickness	Recorded at both ends at each quadrant (i.e. eight values) using digital callipers (refer to **Figure 3**)	mm	0.01 mm
Length	Recorded using a standard tape measure	mm	1 mm
Mass of whole specimen	Recorded using digital scales	kg	0.01 kg
Moisture content	Recorded using Brookhuis FMC microprocessor controlled moisture meter on setting 1	%	0.1 %
Natural frequency	Recorded using Brookhuis MTG Timber Grader	Hz	1 Hz
From the four-point bending test			
Load-deflection graph	Load at mid-span v. deflection at mid-span. Mid-span deflection reduced by average of deflection at left and right supports. All readings recorded and hydraulic actuator operated using a Si-Plan 32 bit Servo controller. Loading rate: 0.5mm/s.	kN mm	1% accuracy / 0.03% accuracy
Failure mode	Photographic evidence of each failure was recorded, alongside the location. Interpretation of failure modes discussed in Table 8.	-	-
Point load deflection			
Deflection	Recorded using a digital dial gauge	mm	0.01 mm

5.1 Measurement of density

The procedure contained in ISO 22175-1 (ISO, 2004b) for measuring the density of a specimen only allows for density to be determined at a single discrete location and therefore does not take into account the variation in density along the length of a specimen (Trujillo and López 2016). Due to this limitation, for the purposes of this investigation, density is estimated based on a representation of the culm as a hollow cylinder, as per Equation 1. This method of estimating density was presented in a previous investigation undertaken at Coventry University (Walker 2015) on fifteen samples of Guadua a.k.

This approximation to a cylinder allows for linear taper of both wall thickness (t) and external diameter (D), but ignores the slight bulging that occurs at the nodes, the presence of the diaphragms to the interior of the node and the fact that taper can be non-linear; a visual representation is provided in Figure 4.

Figure 4: Visual representation of a bamboo culm approximated as a hollow cylinder



To calculate the volume of each specimen, based on the assumption that specimens can be assumed to be of an equivalent volume to a hollow cylinder, Equation 1 uses mean diameter (D_{mean}) and mean wall thickness (t_{mean}).

$$V = l_{sp} \times \frac{\pi}{4}\left[{D_{mean}}^2 - (D_{mean} - 2t_{mean})^2\right] \qquad \textbf{(1)}$$

Where

V is the volume in mm^3

l_{sp} is the length of the specimen in mm,

D_{mean} is the average diameter as explained in Table 4 and calculated thus: $\left[\frac{\sum_{i=1}^{4} D_i}{4}\right]$, in mm,

t_{mean} is the average wall thickness as explained in Table 4 and calculated thus: $\left[\frac{\sum_{i=1}^{8} t_i}{8}\right]$, in mm.

Using Equation 1, the density of each specimen is estimated as shown in Equation 2.

$$\rho = \frac{m}{l_{sp} \times \frac{\pi}{4}\left[{D_{mean}}^2 - (D_{mean} - 2t_{mean})^2\right]} \qquad \textbf{(2)}$$

Where

ρ is the density in g/mm^3,

m is the mass in g.

The only method that could have been used to determine the volume of a specimen taking into account the non-uniform geometry of bamboo and the presence of nodes is by immersion in a water volume-meter as recommended in ISO 22157-2 (ISO 2004c). However this method is deemed inappropriate for this investigation because it would be destructive; due to space restrictions and the impracticality of using a large enough water tank, specimens would have to be cut into smaller pieces and the requirement of such a large tank would not be practically viable if a simple grading procedure is to be proposed.

Furthermore, there is the issue of water absorption into the specimens meaning that moisture content would increase and the mechanical properties of the dry material would be altered.

The accuracy of the cylindrical approximation was demonstrated by Walker (2015) where the volume of fifteen culms of Guadua a.k. were measured using both the cylindrical approximation method and by immersion in water. The mean error in estimation of volume was found to be -7.39% with a standard deviation of 4.77% based on Equation 3 (Walker 2015). The cylindrical method consistently underestimates the volume of the culm, which results in an overestimation of density and for the purposes of this investigation, this inaccuracy has been deemed acceptable.

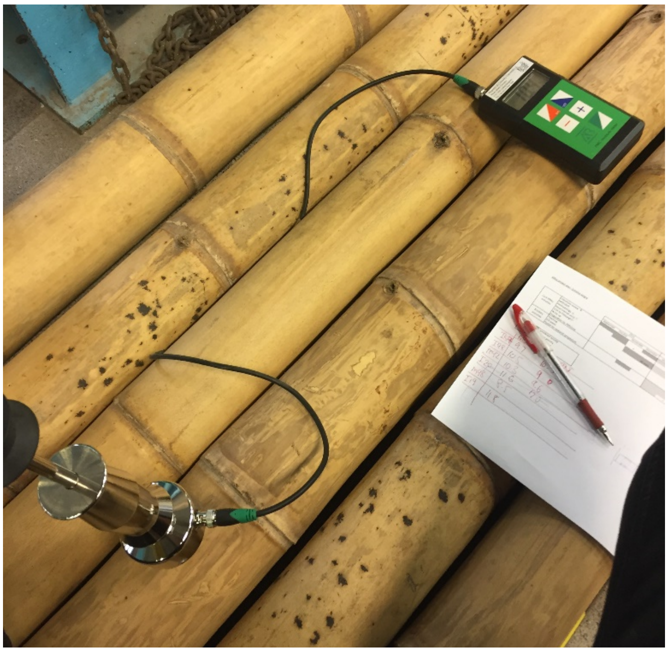
$$Volume\ error = \frac{Volume\ as\ cylinder - Volume\ from\ immersion}{Volume\ from\ immersion} \times 100 \qquad \textbf{(3)}$$

5.2 Measurement of moisture content

The prescribed procedure for the determination of moisture content contained in ISO 22157-1 (ISO, 2004b) requires moisture content to be calculated from the loss in mass resulting from oven-drying specimens. Similarly to the issues identified with establishing volume by immersion in a water volume-meter, this technique is time consuming and impractical for use in a simple grading procedure. Furthermore, it would only be possible to oven-dry small specimens and the resulting estimation of moisture content would only be correct at the discrete location tested. For the purposes of this investigation, a pinned microprocessor controlled moisture meter is therefore used instead; Figure 5

shows the Brookhuis FMC 111.502 microprocessor controlled moisture meter used to obtain readings.

Figure 5: Brookhuis FMC 111.502 microprocessor controlled moisture meter



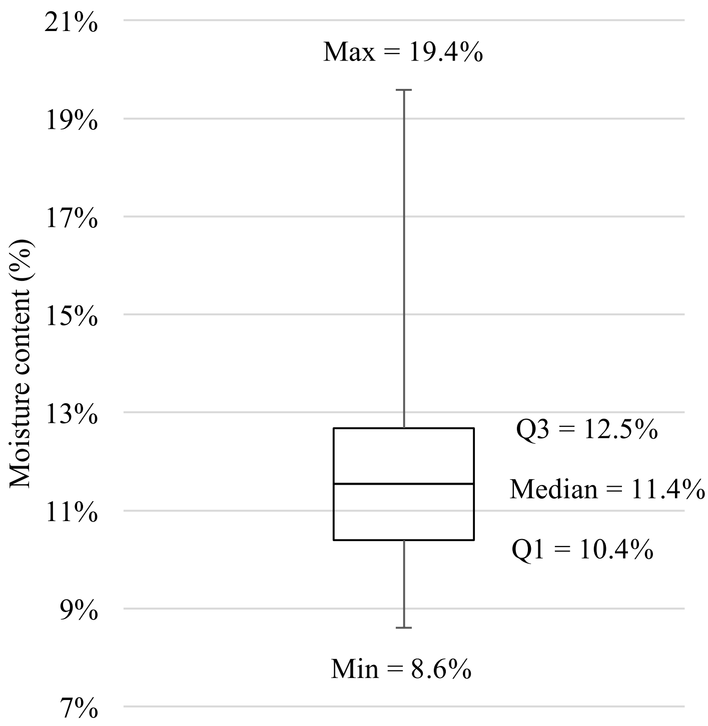
The validity of moisture meter readings was investigated for sixteen specimens of Guadua a.k. and Phyllostachys pubescens (Moso) in a previous investigation carried out at Coventry University (Gibson 2015). Table 5 summarises the investigation to determine the most appropriate setting on the Brookhuis FMC moisture meter (Gibson 2015); Setting 1 was found to give the most accurate results when compared with the results for moisture content obtained from the oven-drying method. Gibson (2015) also established that inserting the probes perpendicular to the fibre direction provided the most accurate results as shown in Table 6. However, due to the curved outer surface of bamboo culms, the probes were prone to damage from bending when hammered into the specimens and it was therefore recommended that the probes should be inserted at an angle of 45° to the fibre direction (Gibson 2015).

Table 5: Summary of preliminary exercise to select correct setting on FMC moisture meter (Gibson 2015)

Table 6: Summary of exercise to corroborate validity of moisture meter readings (Gibson, 2015)

In this investigation, the moisture content of each specimen is measured at three points along the length of the specimen using the Brookhuis Moisture Meter (with an accuracy of ±0.3%) to obtain an average value. Test data adjusted to a 12% moisture content showed little variation from the raw data because most specimens were found to have a moisture content very close to this; all specimens used in this study fell within the range 8.6% - 19.4% and adjustment to 12% was therefore found to be unnecessary. For the total sample of 286 specimens, the mean moisture content was 11.9% with a standard deviation of 2.1%. Moisture content readings for the sample are summarised in the box plot in Figure 6.

Figure 6: Box plot for moisture content data



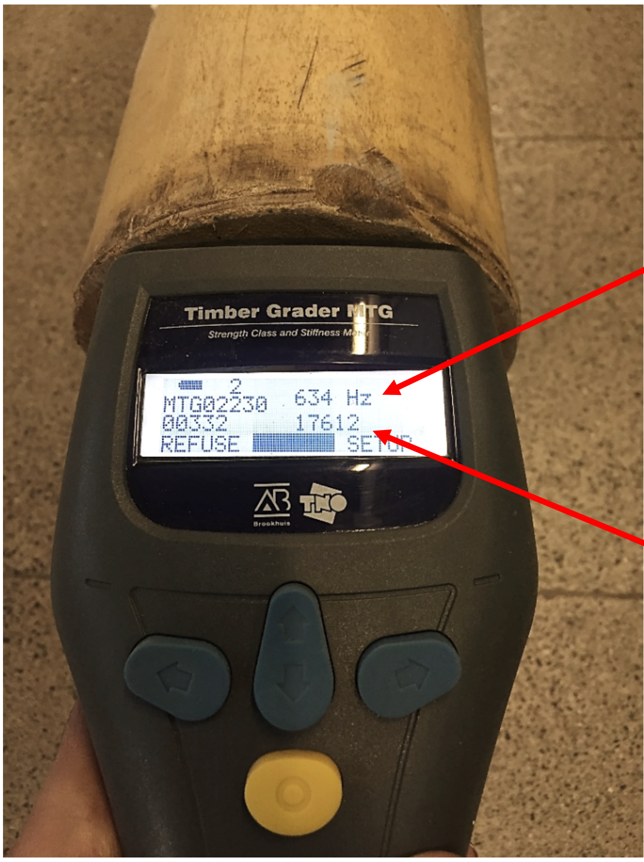
5.3 Measurement of dynamic modulus of elasticity

As demonstrated by Lin, Tsai and Wang (2006), measurement of dynamic modulus of elasticity (E_d) using an ultrasonic wave test instrument combined with drilling resistance techniques was found to provide adequate results for bamboo and positive linear relationships were established between E_d against ρ, $E_{m,s}$ and $f_{m,0}$. It was therefore deemed necessary to further investigate the potential use of a similar handheld non-destructive grading instrument for potential use in a grading procedure.

The chosen instrument was a Brookhuis Timber Grader MTG as shown in Figure 7; a hand held device developed by Brookhuis Micro-Electronics and TNO and approved for use in Europe. This instrument is typically used in timber strength grading to give the user a value for E_d of a specimen based on a number of parameters. The MTG works by propagating sound waves through the specimen and calculating the wave velocity based on an input of length, moisture content, cross-sectional dimensions, mass, density and timber type.

Figure 7: Brookhuis Timber Grader MTG in use

Sound wave propagated from the MTG device through the length of the specimen



Fundamental frequency reading (f_l)

Dynamic modulus of elasticity (E_d) – only useful for timber specimens

The MTG is only designed for use with timber and uses a pre-set value for density based on the species of timber it is being used on. For the purposes of this investigation, bamboo was approximated as a hardwood with a density of 650 kg/m^3. Calculated density (based on an approximation of volume as described in Section 5.1) for specimens used in this study range from approximately 427 kg/m^3 to 934 kg/m^3 with an average of 681 kg/m^3 for the sample.

The MTG assumes a rectangular cross-section and therefore only allows the user to input measurements of depth and breadth. Depth and breadth were therefore estimated so that the MTG uses a square cross-section equivalent to the circular-hollow bamboo specimen being tested as proposed by Gibson (2015) who carried out a previous investigation with the MTG at Coventry University.

Due to the susceptibility to errors resulting from the assumptions regarding density and cross-sectional area, the dynamic modulus of elasticity readings from the MTG cannot be used with confidence and must be disregarded. Instead, the output fundamental frequency of the acoustic stress wave (f_1) is used as it is less susceptible to errors due to it being dependant only on the input measurement of length. Fundamental frequency (f_1) is then used to calculate the dynamic modulus of elasticity of the specimen as set out in Equation 4 (Gibson 2015).

Readings of f_1 were taken from both ends of each specimen and repeated until the same frequency reading was obtained at each end. A consistent reading at both ends provided assurance that the measured frequency was correct because the velocity of the stress wave propagating through the specimen must be the same regardless of the direction of travel.

$$E_d = v^2\rho \qquad \textbf{(4)}$$

Where

ρ is the density calculated as in Equation 2

v is the speed of sound in the specimen calculated from Equation 5.

Such that:

$$v = 2l_{sp}f_1 \qquad \textbf{(5)}$$

Where

l_{sp} is the total length of the specimen

f_1 is the fundamental frequency of the specimen determined using the Brookhuis MTG (refer to Figure 7 where the fundamental frequency in Hz is shown on the MTG display).

5.4 Measurement of static bending properties

As discussed, bending tests are universal in timber strength grading due to the significance of bending strength $f_{m,0}$ and static modulus of elasticity $E_{m,s}$ in the design of timber elements and frames. The same is true for bamboo and bending tests were therefore considered essential in the proposal of a grading procedure. Though bending tests for bamboo date back to the 1920s (Janssen 1991), it was Gnanaharan, Janssen and Arce (1994) who first identified the potential to infer $f_{m,0}$ and $E_{m,s}$ from data that had been measured non-destructively such as diameter and density. The correlations obtained were reportedly very strong, although based on a sample of only twelve specimens.

For the determination of static bending properties in this investigation, a four-point bending test is conducted on each specimen, based on the procedure outlined in Clause 10 of ISO 22157-1 (ISO, 2004b) with some modifications. The configuration of the testing rig is shown in Figure 8.

A Si-Plan Servo controller is used to operate the hydraulic actuator and load cell similarly to Gibson (2015) with loading applied at a constant 0.5 mm/s as prescribed in ISO 22157-1 (ISO 2004b). Point loads are applied through two pinned transfer beams at a distance of 500 mm from the mid-point of the free span. This is the first modification to the procedure in ISO 22157-1 (ISO 2004b) whereby loads are not necessarily placed in thirds and instead it is ensured that the shear span (a) as shown in Figure 8, always exceeds ten times the diameter of the specimen. The shear span was fixed at 1150 mm and the free span (L) was fixed at 3300 mm for all specimens tested in this investigation.

Another modification to the procedure prescribed in ISO 22157-1 (ISO 2004b) is that fabric straps are attached to the transfer beams and supports to distribute the load and minimise the risk of localised crushing. The rig is fixed to the concrete floor with steel supports. This configuration was also employed by Gibson (2015).

A data acquisition system is used to collect continuous readings of the applied load and displacement at the mid-span and supports; measurements of displacement are obtained using LVDTs. The inclusion of LVDTs at the supports in addition to an LVDT at mid-span is another modification to the prescribed procedure contained in ISO 22157-1 (ISO 2004b); it was felt necessary to include these additional LVDTs so that any local deformation at the supports could be subtracted from the total deflection of the specimen to give the true deflection of the specimen. ISO 22157-1 (ISO 2004b) states that the apparatus for bending tests must measure load to the nearest 1% and displacement to the nearest millimetre which is satisfied by this test configuration.

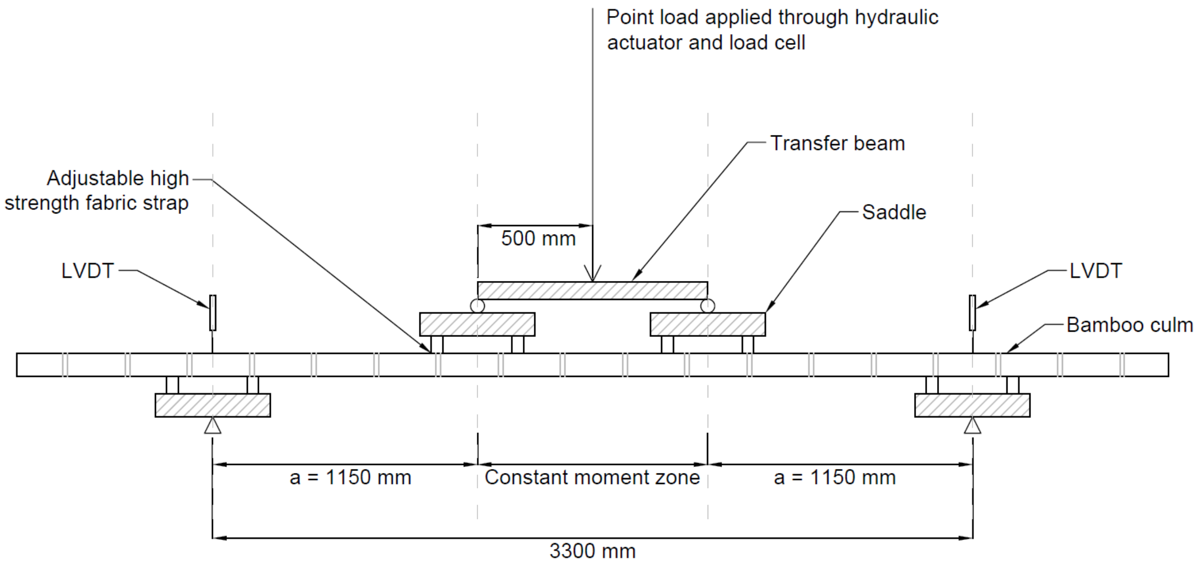
After configuration and prior to the commencement of any tests, the validity of modulus of elasticity measurements is checked by carrying out a dummy test. This requires loading and unloading specimens to check the consistency of the measurements; the dummy test gave the same modulus of elasticity each time load was applied to a specimen and therefore demonstrates that the experiment is robust.

For each specimen the applied load and displacement at mid-span is recorded, in addition to the observed failure mode and the location of the failure. Failures that occurred within the constant moment region as shown in Figure 8, are treated as failures in bending. The constant moment region refers to the region where the maximum bending moment is observed and is a constant value; this is in contrast to a three-point bending test where the maximum moment is achieved at the point of load application and is not a constant value.

Bending failures as summarised and explained further in Table 8, included tensile failures, compressive failures, collapse of the culm or one of these occurring at the location of a support.

Failures that occurred in either shear span and classified as a shear failure are excluded from bending moment and bending moment calculations, but are included in stiffness and static modulus of elasticity calculations.

Figure 8: Configuration of four-point bending test with modifications to Clause 10 of ISO 22157-1 (ISO 2004b)



For the analysis of results, the second moment of area, I_B for each specimen is calculated using Equation 6 from ISO 22157-1 (ISO 2004b).

$$I_B = \frac{\pi}{64}\left[{D_{mean}}^4 - (D_{mean} - 2t_{mean})^4\right] \qquad \textbf{(6)}$$

Where

D_{mean} is the average external diameter of the culm,

t_{mean} is the average wall thickness of the culm.

For specimens which are classified as bending failures, as detailed in Table 8, $f_{m,0}$ is calculated by Equation 8 from the maximum applied bending moment on the specimen as per Equation 7:

$$M_{max} = \frac{F_{ult} \times a}{2} \qquad \textbf{(7)}$$

Where

F_{ult} is the maximum applied load (the total load applied onto the two points of load),

a is the shear span (fixed at 1150 mm), i.e. the distance from one support to the nearest point of load application as shown in Figure 8.

The bending strength parallel to the fibres, $f_{m,0}$, is calculated from:

$$f_{m,0} = \frac{M_{max} \times D_{mean}}{2 \times I_B} \qquad \textbf{(8)}$$

Where

M_{max} as calculated in Equation 7,

D_{mean} is the average external diameter of the culm,

I_B is the second moment of area, as defined in Equation 6.

The flexural stiffness from of the section, $EI_{m,s}$, is determined from Equation 9:

$$EI_{m,s} = \frac{(F_{60} - F_{20}) \times a(3L^2 - 4a^2)}{48(\delta_{60} - \delta_{20})} \qquad \textbf{(9)}$$

Where

F_{20}, F_{60} is the applied load at 20% and 60% of F_{ult} respectively, though in some instances different values were used to ensure that only linear behaviour of the specimen was included,

δ_{20}, δ_{60} is the deflection at mid-span at 20% and 60% of the deflection attained at F_{ult} respectively, though if the values for F were changed, these would be changed correspondingly,

L is the full clear span (note that it is not the same as l_{sp}),

F_{ult} as previously defined,

a as previously defined,

$E_{m,s}$ was calculated simply by dividing Equation 9 by Equation 6.

As per Equation 9, the applied load and deflection at mid-span corresponding to 20% and 60% of F_{ult} are used in the calculation of $EI_{m,s}$. The region between 20% and 60% is considered to represent bending in the elastic zone and is characterised by a constant gradient on the load vs. deflection graph (a linear relationship between load and deflection). ISO 22157-2 (ISO 2004c) suggests that *"in most cases, a linear part of the load-deformation diagram can be found between 20% and 80% of the ultimate strength"* however for the majority of specimens tested in this investigation, linear behaviour was found to occur between 20% and 60% of F_{ult} rather than in the region 20% to 80%. In some cases the 20%-60% range was adjusted further to ensure that only linear behaviour was considered.

5.5 Measurement of point-load deflection

In practice, a four-point bending test is unlikely to be feasible due to the expense and size of the required test equipment. Therefore, a simple experiment is investigated whereby a lump mass is hung from the specimen and increased incrementally whilst measuring the deflection at mid-span.

Readily available fabric straps are used to hang the load on each specimen and deflection is measured using a digital dial gauge as detailed in Table 4. The use of a tape measure was considered however this would only allow measurements to be taken to the nearest millimetre and therefore would not provide adequate precision in the measurements. Figure 9 illustrates the test configuration and Figure 10 shows the test in progress.

The point-load deflection test is carried out on a limited sample prior to subjecting each specimen to the destructive four-point bending test so that the modulus of elasticity determined by both methods could be compared and the validity of the point-load deflection test could be investigated.

Figure 9: Test configuration for measurement of point load deflection

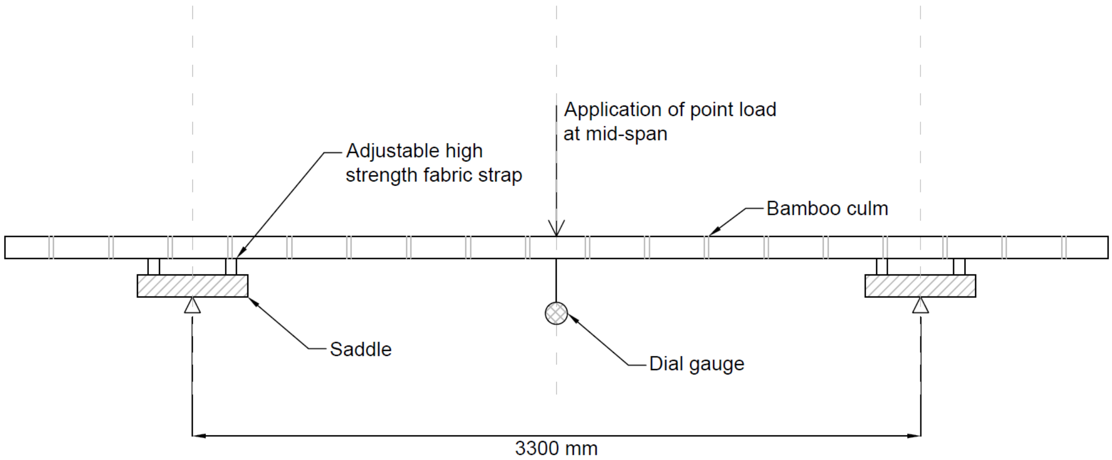


Figure 10: Photograph of point load deflection test

6 Results

The point load deflection test is a novel approach presented as an alternative to the four-point bending test, however the four-point bending and dynamic tests follow a methodology previously established at Coventry University. The results and analysis presented in the following sections are original and provide a unique insight into the flexural properties of full-culm round bamboo.

Table 7 summarises the experimental results obtained during the investigation for diameter, wall thickness, density, dynamic and static modulus of elasticity, bending strength, shear strength and moisture content. A complete set of results from the experimental programme is given in Appendix B.

The first observation that can be drawn from the summarised results is that the observed densities are in line with expectations for bamboo. Furthermore, trends observed in studies on other species (Trujillo and López 2016) where density was found to increase with age and position along the culm are confirmed by this investigation.

Strength and stiffness values for the sample are also similar to previously published results for Guadua a.k. (Trujillo and López 2016); the values obtained in this investigation are slightly higher than the published data however it is likely that this could be a result of the lower moisture content of the sample used in this investigation. The positive trends observed for bending strength and static modulus of elasticity against age and position along the culm are also similar to the observations previously published in other studies (Trujillo and López 2016).

The mean static and dynamic modulus of elasticity for the sample were found to be fairly close, suggesting that the dynamic test conducted using the Brookhuis MTG could provide a useful estimation of static bending properties if the data is well correlated.

At first glance, the large coefficient of variation observed for wall thickness suggests that the data could be unreliable however this is explained by the inclusion of specimens from varying positions along the culm in the sample.

Table 7: Summary of experimental results

Property	**D_{mean} (mm)**	**t_{mean} (mm)**	**ρ (kg/m^3)**	**E_d (N/mm^2)**	**$E_{m,s}$ (N/mm^2)**	**f_m (N/mm^2)**	**f_v (N/mm^2)**	**Moisture Content (%)**
Sample size	286	286	286	229	242	181	61	286
Mean	99.9	12.4	681	18175	17808	77.0	5.55	11.87%
SD	14.1	4.2	103	2759	4089	21.5	1.43	2.08%
CoV	14.17%	33.85%	15.20%	15.18%	22.96%	27.88%	25.80%	17.56%

Despite observing a shear span of ten times the diameter of every specimen, not all specimens exhibited a bending failure with 21% (61 specimens) instead failing in shear (f_v) as detailed in Table 8. Five failure modes are observed in the constant moment zone between the two points of load application and these failure modes are treated as bending failures in the analysis. It could be argued that not all of these are strictly pure bending failures and instead exhibited a more complex failure mechanism, therefore explaining the large standard deviations observed for bending strength, $f_{m,0}$ in Figures 19 and 20.

Table 8 provides a description of each failure mode together with the frequency of occurrence. Figures 11 to 15 show examples of each failure mode.

Table 8: Observed failure modes

Type	**Failure mode**	**Description**	**Figure**	**Frequency (%)**
Shear	-	Shear plane between fibres. Always present in shear span	Figure 11	21%
Bending	Compression	Culm kinks, with crushing of fibres to topside, splitting may be present	Figure 12	13%
	Collapse of culm	Integrity of culm is lost through tension perpendicular to fibres failure.	Figure 13	14%
	Failure under support	Crushing of culm under load application straps	Figure 14	45%
	Combined	Combination of any two bending mechanisms	-	5%
	Tension failure	Failure of fibres to underside of specimen	Figure 15	1%
Total				100%

Figure 11: Typical shear failure

Figure 12: Typical compression failure

Figure 13: Typical culm collapse

Figure 14: Typical failure under loading straps

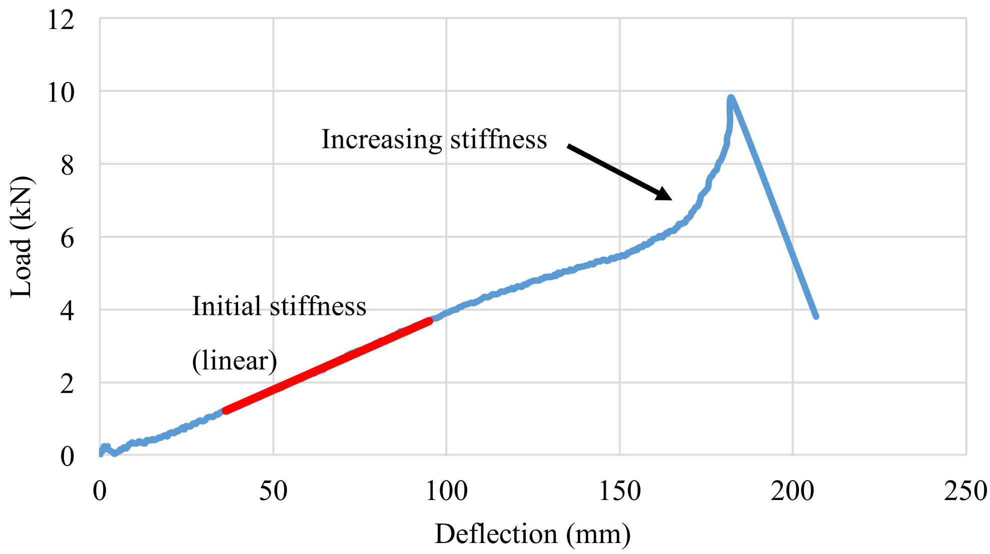
Figure 15: Typical tension failure

6.1 Erroneous results

Figure 16 shows an example of one load vs. deflection graph where the specimen exhibited an increase in stiffness during the four-point bending test. This occurred in only seventeen specimens (6% of the sample), almost exclusively in cases where a shear failure was induced. In these cases, the results of the bending test were not used to calculate moment capacity (M_{max}). For all other specimens in the sample, the criteria for failure was straightforward with specimens behaving as per Figure 18.

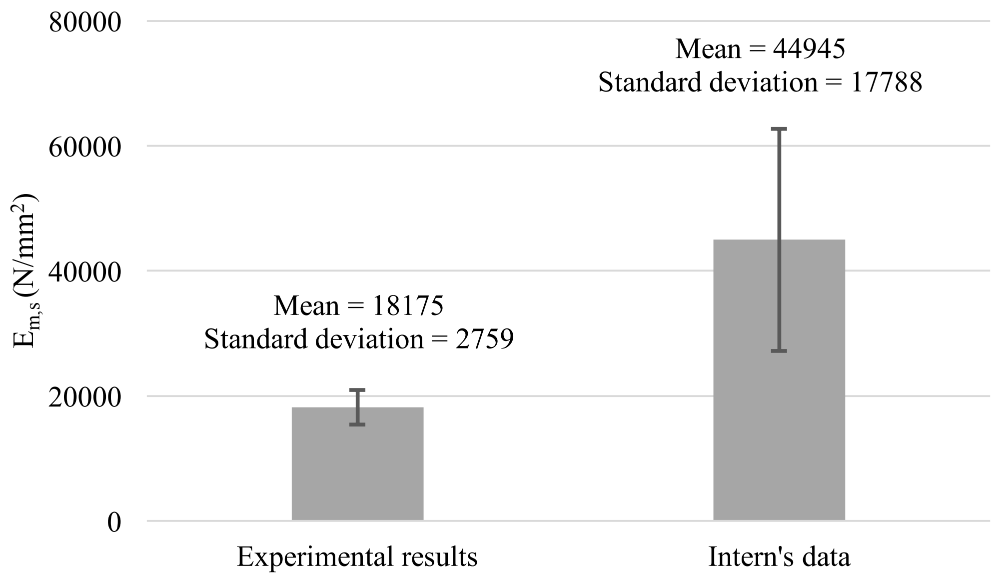
The apparent increase in stiffness as shown in Figure 16 occurs due to the interaction of the supports which provide additional stiffness to the specimen by preventing it from being able to slide smoothly through the supports of the bending rig as the culm deflects. The interaction of the supports distorts the results and in these cases and only the initial linear stiffness is considered, as illustrated by the red line in Figure 16.

Figure 16: Example load vs. deflection graph with specimen exhibiting an increase in stiffness



For 39 of the bending tests conducted, the results for modulus of elasticity $E_{m,s}$ (and therefore $EI_{m,s}$), moment capacity M_{max} and bending strength $f_{m,0}$ have been discounted from the analysis. These tests were conducted by an intern at Coventry University prior to the commencement of this investigation and whilst it was felt that all available data should be used in the analysis, these particular tests could not be included as the values obtained by the intern for static modulus of elasticity were significantly larger than the expected values for Guadua a.k as shown in Figure 17. It was not possible to establish why the values were incorrect because the errors were not consistent. These 39 tests are therefore discounted from any analysis concerning bending properties, however values for D_{mean}, q_{test}, ρ, E_d and EI_d are used where appropriate as reflected in Table 7.

Figure 17: Comparison of intern's data against experimental results as reported



6.2 Calculation of mechanical properties

To demonstrate the calculation steps required to establish the mechanical properties of the sample, an example is provided below using specimen I45. Raw data for top and bottom dimensions are obtained as per Figure 3.

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Total length of specimen:		4441 mm
Mass:		14.94 kg
Top dimensions	D_1:	118.67 mm
	D_2:	119.33 mm
	t_1:	18.34 mm
	t_2:	17.26 mm
	t_3:	16.13 mm
	t_4:	18.92 mm
Bottom dimensions	D_3:	123.05 mm
	D_4:	121.01 mm
	t_5:	19.06 mm
	t_6:	23.82 mm
	t_7:	21.02 mm
	t_8:	22.39 mm

Average external diameter is calculated as the average of the four measurements of diameter (two measurements at each end of the specimen) taken as per Figure 3.

$$D_{mean} = \frac{118.67 + 119.33 + 123.05 + 121.01}{4} = 120.52\ mm$$

Similarly, average wall thickness is calculated as the average of eight measurements (four readings at each end of the specimen):

$$t_{mean} = \frac{18.34 + 17.26 + 16.13 + 18.92 + 19.06 + 23.82 + 21.02 + 22.39}{8} = 19.62\ mm$$

Using Equation 1, the volume of the specimen is approximated as follows:

$$V = 4441 \times \frac{\pi}{4}\left(120.52^2 - (120.52 - (2 \times 19.62)^2)\right) = 27615614.58\ mm^3$$

Density is calculated by substituting the estimated volume into Equation 2:

$$\rho = \frac{14.94}{27615614.58 \times 10^{-9}} = 540.99\ kg/m^3$$

The reading of fundamental frequency obtained through the dynamic test is then used to calculate the speed of sound travelling through the specimen and the dynamic modulus of elasticity. For specimen I45, the fundamental frequency was recorded as 571 Hz based on a moisture content of 11.1% (the average of three moisture content readings along the specimen).

Speed of sound wave travelling through specimen is calculated from Equation 5 as:

$$v = 2 \times (4441 \times 10^{-3}) \times 571 = 5071.62\ mm/s$$

Dynamic modulus of elasticity is calculated from Equation 4 as:

$$E_d = 5071.62^2 \times 541 \times 10^{-6} = 13915.21\ N/mm^2$$

From the static bending test, the maximum applied load on specimen I45 (recorded from the Si-plan Servo controller) was 18982 N for a shear span of 1150 mm. This is used to calculated the maximum bending moment as per Equation 7:

$$M_{max} = \frac{(18982\times10^{-3})\times(1150\times10^{-3})}{2} = 10.91\ kNm$$

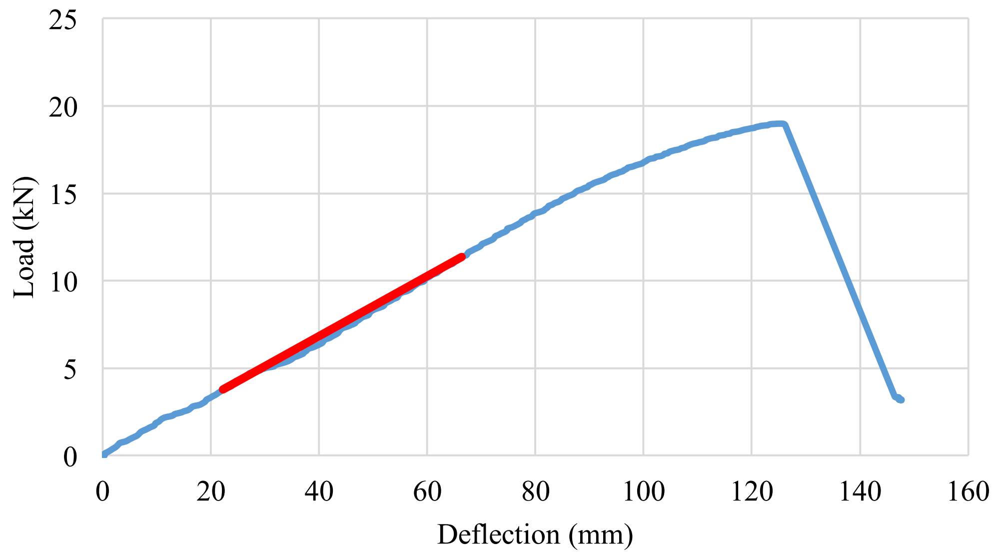
The second moment of area of specimen I45 is calculated from Equation 6 and bending strength is calculated from Equation 8 as follows:

$$I_B = \frac{\pi}{64}(120.52^4 - (120.52 - (2\times19.62)^4) = 8212203.34\ mm^4$$

$$f_{m,0} = \frac{10.91\times10^6\times120.52}{2\times8212203.34} = 80.09\ N/mm^2$$

The calculation for flexural stiffness in bending is based on the load vs. deflection graph shown in Figure 18 which is plotted from the data collected using the Si-plan Servo. The red line shown on the graph illustrates the applied load and resulting deflection between 20% and 60% as calculated in Table 9. The target load is calculated as 20% and 60% of the maximum applied load (as explained in Section 5.4) and the actual load refers to the load closest to the target load, recorded from the Si-plan Servo.

Figure 18: Load vs. deflection for Specimen 'I45'



As discussed in Section 5.4, the deflection values used for calculation of static bending properties refer to the true deflection of the specimen whereby displacements at the supports, as measured by the LVDTs, are averaged and then subtracted from the deflection experienced at midspan.

Table 9: Calculation of applied load and deflection at 20% and 60%

	Target load (kN)	Actual load (kN)	Deflection (mm)
20%	3.8	3.77	22.2
60%	11.4	11.4	66.3
Δ Load		7.58	
Δ Deflection			44.1

Based on Figure 18 and Table 9, the flexural stiffness in bending of specimen I45 is calculated using Equation 9:

$$EI_{m,s} = \frac{(11.36 - 3.77)\times 10^3 \times 1150 \times ((3\times 3300^2) - (4\times 1150^2))}{48\times(66.31 - 22.25)} = 1.13\times 10^{11}\ Nmm^2$$

6.3 Seeking strong correlations

In order to develop a robust grading procedure for bamboo, it is necessary to establish reliable correlations between destructively and non-destructively measured properties. Simple linear correlations are sought between bending strength, $f_{m,0}$ against the non-destructively measured properties recorded for the sample; a complete set of results are provided in Appendix B.

Figures 19 and 20 show the data for static modulus of elasticity and density plotted against bending strength which are relationships that are commonly used in timber strength grading. The R^2 values demonstrate the strength of these relationships; $R^2 = 1$ tells us that there is a perfect correlation between the variables and $R^2 = 0$ tells us that there is no correlation between the variables. For both density and static modulus of elasticity against bending strength, R^2 was found to be between 0.4 and 0.5 which is not particularly compelling. The relationship observed between static and dynamic modulus of elasticity, as shown in Figure 21, was similarly weak.

These weak correlations can partly be explained by the geometric uncertainty in the analysis. Similarly to the variation observed for volume with changing position along the culm as discussed in Section 5.1, the second moment of area, I_B, also varies along the culm, and Equation 6, is therefore only an approximation. As proposed by Nugroho and Bahtiar (2013), this geometric uncertainty could be reduced by building a more rigorous model of the bamboo culms which accounts for the effect of taper, however for the purposes of a simple grading procedure, it is deemed that this level of analysis would not be viable at this stage.

Figure 19: Correlation between $f_{m,0}$, and $E_{m,s}$

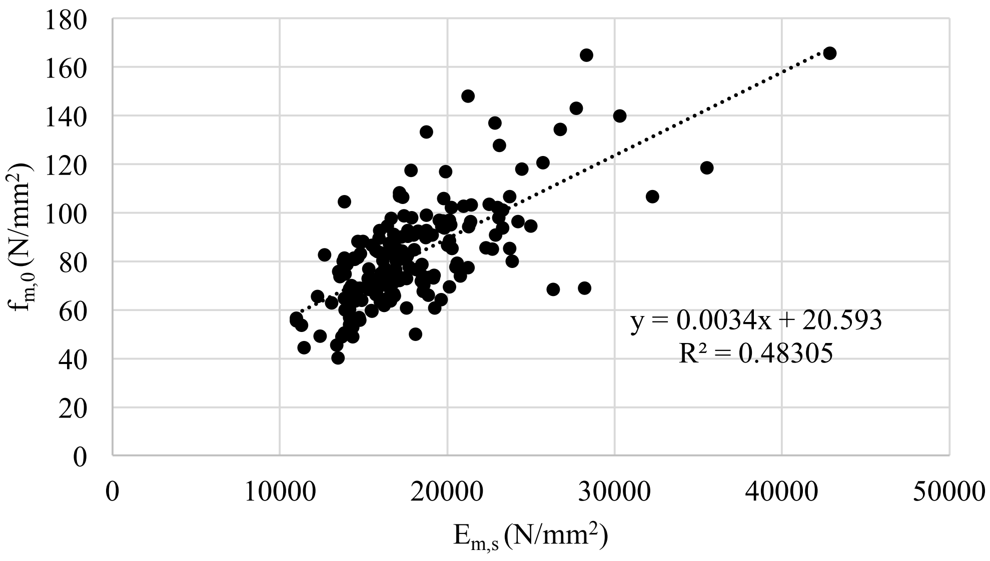


Figure 20: Correlation between ρ and $f_{m,0}$

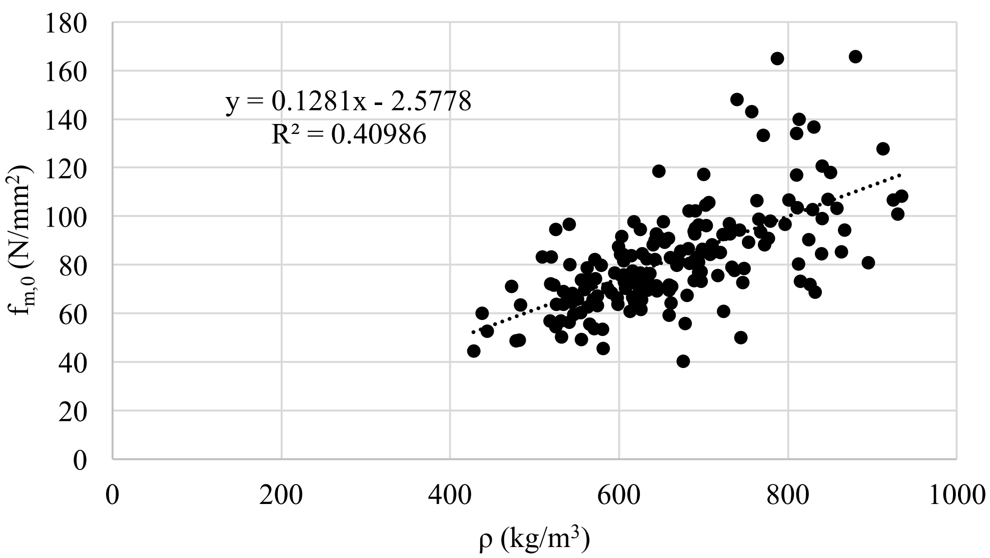
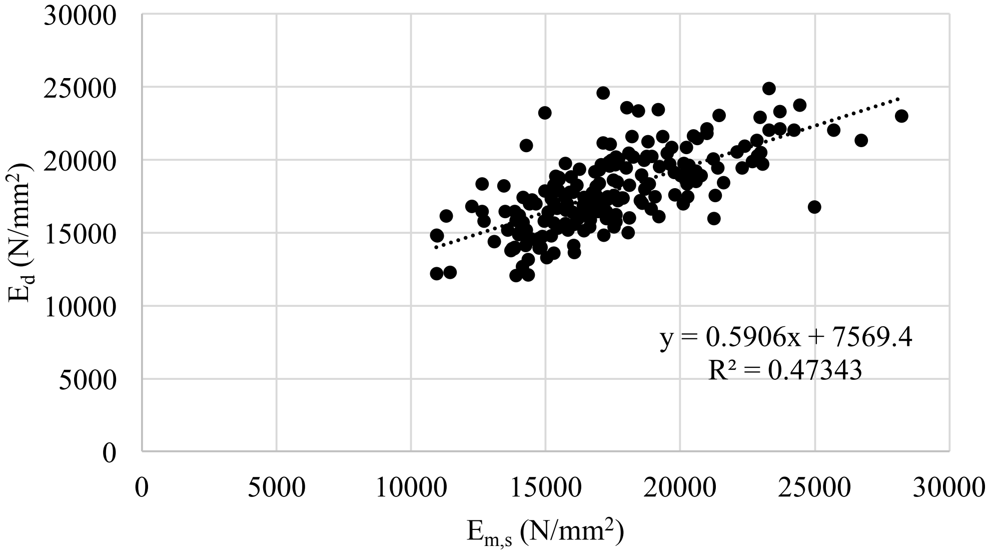


Figure 21: Correlation between $E_{m,s}$ and E_d



Due to the weak correlations observed in Figures 19, 20 and 21, an alternative analysis is explored whereby mechanical properties which do not rely on the approximation of geometric properties are used instead of stress and modulus of elasticity which require the determination of I_B. Maximum bending moment, M_{max} and flexural stiffness, EI are therefore considered in the analysis instead. Using this approach and removing the effect of geometric uncertainties has provided much stronger correlations as illustrated by the relationships shown in Figures 22 and 23 for mass per unit length, q_{test}, and static modulus of elasticity, $EI_{m,s}$ plotted against maximum bending moment where R^2 is improved to around 0.87 for both. The usefulness of this approach is supported by the importance of these mechanical properties in the design of any element subject to flexure.

Figure 22: Correlation between M_{max}, and $EI_{m,s}$

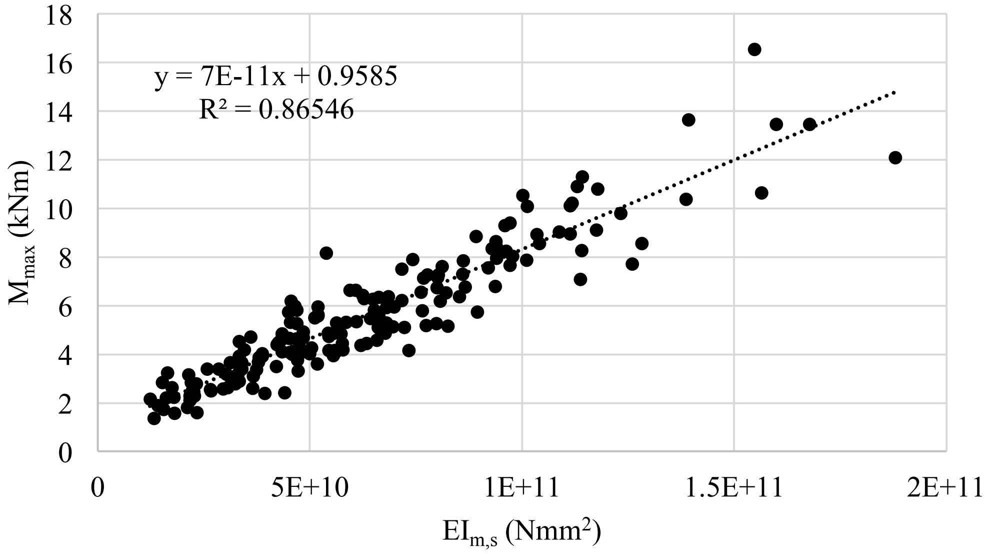


Figure 23: Correlation between M_{max}, and q_{test}

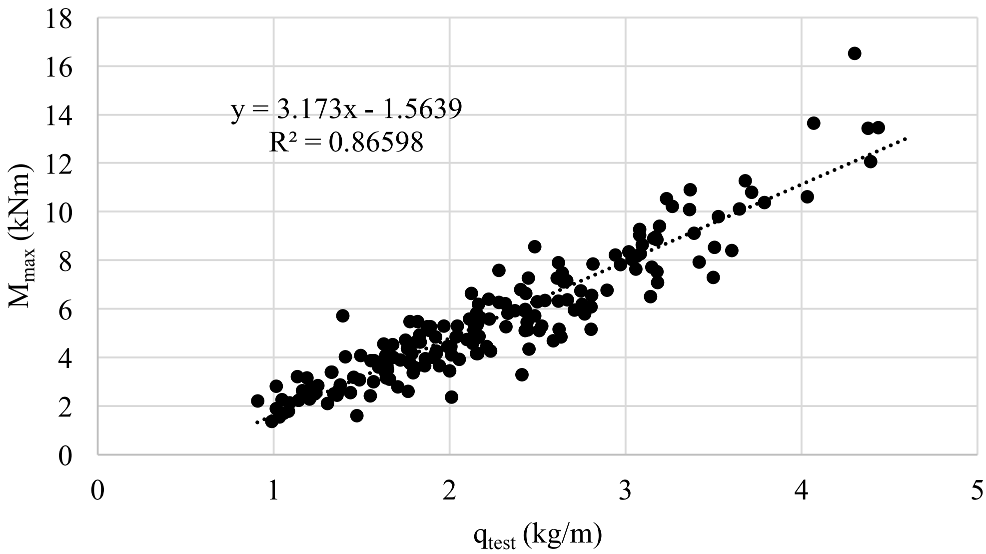
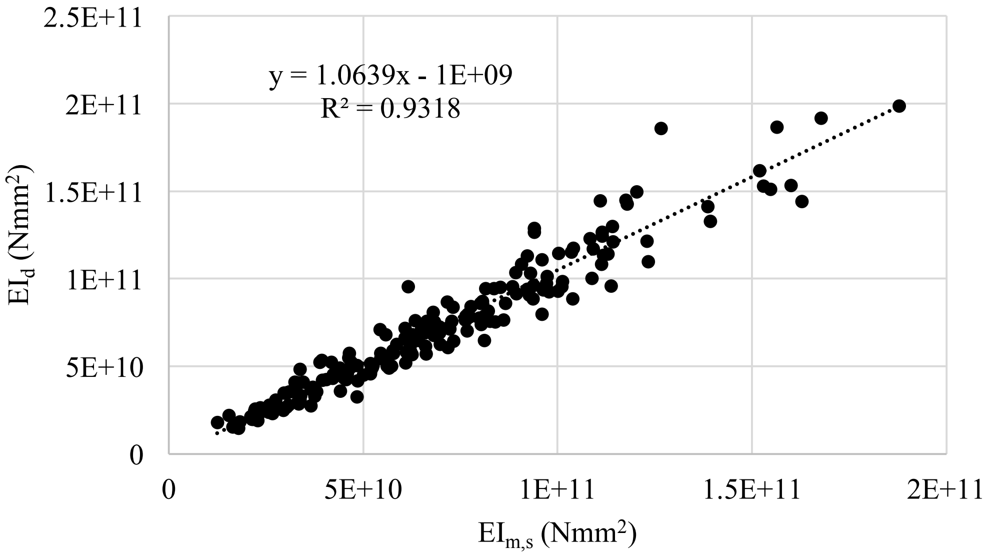


Figure 24 illustrates the extremely strong relationship observed between static flexural stiffness $EI_{m,s}$ and dynamic flexural stiffness EI_d where $R^2 = 0.93$. As detailed in Section 5.4, $EI_{m,s}$ is calculated from Equation 9 which is based on the slope of the load vs. deflection graph obtained during the four-point bending test. Calculation of EI_d comes from the product of Equation 6 for second moment of area and Equation 4 for calculation of dynamic modulus of elasticity based on the measured stress-wave frequency. Whilst both values for flexural stiffness are based on geometric properties, when plotted against one another, the geometric uncertainty is cancelled out by the inclusion of the second moment of area in each term and therefore the impact of such inaccuracies is reduced.

Figure 24: Correlation between $EI_{m,s}$ and EI_d



By substituting Equation 5 in Equation 4 and multiplying by Equation 6, EI_d is equal to:

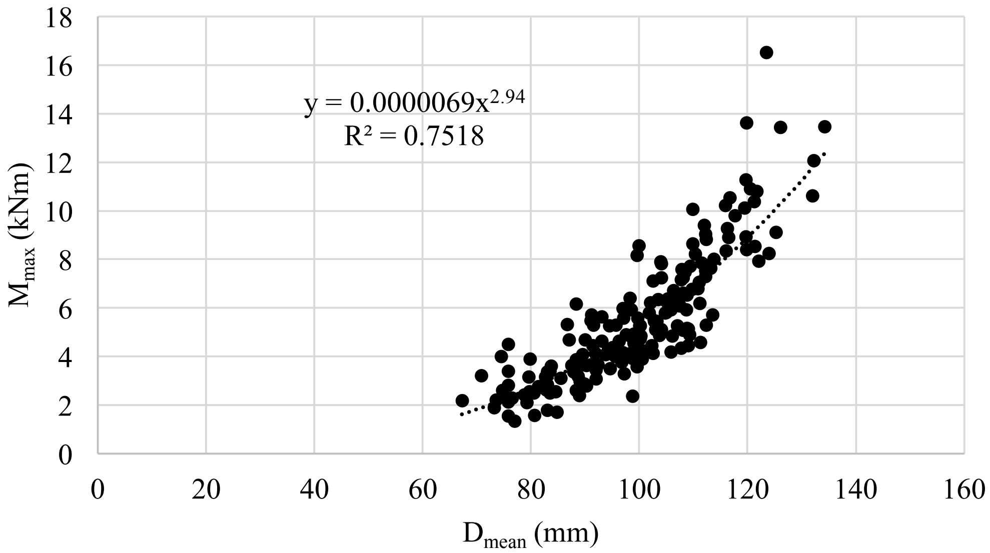
$$EI_d = v^2 \times \rho \times I = \frac{v^2 \times m \times \frac{\pi}{64}\left[D_{mean}{}^4 - (D_{mean} - 2t_{mean})^4\right]}{l \times \frac{\pi}{4}\left[D_{mean}{}^2 - (D_{mean} - 2t_{mean})^2\right]} \qquad \textbf{(10)}$$

Simplifying Equation 10 gives:

$$EI_d = \frac{v^2 \times m \times \left[D_{mean}{}^2 + (D_{mean} - 2t_{mean})^2\right]}{16 \times l} \qquad \textbf{(11)}$$

Another strong relationship is established for maximum bending moment plotted against average diameter D_{mean} as shown in Figure 25. The relationship follows a cubic regression with $R^2 = 0.75$.

Figure 25: Correlation between M_{max}, and D_{mean}



A summary of all the simple linear regressions explored between two variables is contained in Table 10 where it can be observed that q_{test}, $EI_{m,s}$, EI_d and D, are strongly related to M_{max}, and $EI_{m,s}$. Using this bending capacity approach instead of focusing on strength and modulus of elasticity improves the quality of the established relationships with R^2 values ranging between 0.77 to 0.93. This is useful because bending moment capacity and flexural stiffness are vital mechanical properties in the design of any element subject to flexure, such as beams and frames.

Table 10: Summary of simple linear regressions

Variables tested	**R^2 values**	
	$f_{m,0}$	**$E_{m,s}$**
ρ	0.410	0.306
$E_{m,s}$	0.483	-
E_d	0.303	0.473
	M_{max}	**$EI_{m,s}$**
q_{test}	0.866	0.865
EI_d	0.851	0.932
$EI_{m,s}$	0.866	-
D_{mean}	0.773^{+}	0.869^{+}
D_{mean}^3	0.766	0.865
D_{mean}^4	0.771	0.869

$^{+}$polynomial regression

6.4 Multiple regressions

To extend the analysis and explore whether the correlations observed in the simple regression analysis between two variables can be improved, multiple regressions are trialled; the findings are summarised in Table 12. The multiple regressions are conducted on the basis of a 95% confidence interval. In some cases, the model is found to be statistically insignificant (explained in the example provided later in this section) and the relationship is not explored further.

The quality of relationships is in some cases significantly improved when considering multiple variables instead of only two variables as in the simple regressions. This suggests that in a grading procedure for bamboo, it will be valuable to grade on the basis of more than one IP, thereby increasing confidence in the robustness of the grading procedure.

An example of the multiple regression analysis is provided in Table 11 for the correlation between mass per unit length, dynamic modulus of elasticity and maximum bending moment.

Table 11: Multiple regression output for q_{test} and EI_d against M_{max}

Regression Statistics						
Multiple R	0.944					
R Square	0.891					
Adjusted R Square	0.890					
Standard Error	0.922					
Observations	148					
ANOVA						
	df	**SS**	**MS**	**F**	**Significance F**	
Regression	2	1010	506	595	1.24E-70	
Residual	145	123	0.850			
Total	147	1140				
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**
Intercept	-1.14	0.340	-3.36	0.00101	-1.81	-0.469
Mass per unit length (kg/m)	2.38	0.322	7.39	1.06E-11	1.74	3.02
EI Dynamic (Nmm^2)	2.04E-11	6.84E-12	2.98	0.00343	6.83E-12	3.39E-11

The output of the multiple regression analysis as shown in Table 11 contains a number of statistical terms; the most pertinent to this investigation will now be discussed.

In the 'Regression Statistics' section, the analysis produces a Multiple R (or correlation coefficient) value of approximately 0.9441 which is the square root of the R Square value. A correlation coefficient of 1 means that there is a perfect linear relationship and therefore, we can see that the correlation is strong in this case. The R Square value describes how well the data fits the trend line however in this example because we have more than one variable, it is necessary to use the Adjusted R Square value which adjusts the model to account for the additional terms; going forward, R^2 for M_{max} against q_{test} and EI_d should be taken as 0.8899.

ANOVA, or analysis of variance, contains the terms used to calculate the R values discussed previously however the most important value to note in this section is 'Significance F'. The model is only deemed statistically significant if Significance F is smaller than 0.05, which is safely the case in this example. Significance F is derived from the 'P-values' shown in the last section of the table; where the P-value associated with one or more variables is greater than 0.05, the variable is insignificant to the correlation. For multiple regressions where Significance F is greater than 0.05, the model is discarded.

Table 13 summarises the equations derived from the simple and multiple regressions. Only multiple regression where R^2 values exceed those for simple regressions and all variables in the combination are significant have been listed.

Table 12: Summary of multiple regressions

Variables tested	**Adjusted R^2**	
	$f_{m,0}$	$E_{m,s}$
$\rho + E_d$	0.342*	0.469*
$\rho + E_{m,s}$	0.557	-
	M_{max}	$EI_{m,s}$
$q_{test} + D_{mean}$	0.865*	0.887
$q_{test} + D_{mean}^3$	0.867	-
$q_{test} + D_{mean}^4$	-	0.903
$q_{test} + D_{mean} + EI_d$	0.892*	0.944*
$q_{test} + D_{mean} + EI_{m,s}$	0.893	-
$q_{test} + D_{mean}^3 + EI_d$	0.893*	0.944*
$q_{test} + D_{mean}^3 + EI_{m,s}$	0.892*	-
$q_{test} + D_{mean}^4 + EI_d$	-	0.944*
$D_{mean} + EI_d$	0.850*	0.932*
$D_{mean} + EI_{m,s}$	0.864*	-
$q_{test} + EI_d$	0.890	0.944
$q_{test} + EI_{m,s}$	0.865*	-

*The P-value for one of the variables in the combination is not significant

Table 13: Equations for strong correlations

	M_{max} (kNm)	**$EI_{m,s}$ (Nmm^2)**
q_{test} (kg/m)	$= (3.17\times q_{test}) - 1.56$	$= (3.84\times 10^{10}\times q_{test}) - 2.47\times 10^{10}$
EI_d (Nmm^2)	$= \left(7.00\times 10^{-11}\times EI_{m,s}\right) + 1.08$	$= (1.06\times EI_d) + 1\times 10^9$
$EI_{m,s}$ (Nmm^2)	$= \left(7.00\times 10^{-11}\times EI_{m,s}\right) + 0.959$	-
D_{mean} (mm)	$= (0.00256\times D^2) - (0.343\times D) + 13.9$	$= (3.15\times 10^7\times D^2) - (4.09\times 10^9\times D) + 1.51\times 10^{11}$
D_{mean}^4 (mm^4)	$= (4.01\times 10^{-8}\times D^4) + 1.19$	$= (526\times D^4) + 5.00\times 10^9$
q_{test} (kg/m) + D_{mean}^4 (mm^4)	-	$= (1.95\times 10^{10}\times q_{test}) + (281\times D^4) - 1.28\times 10^{10}$
q_{test} (kg/m) + EI_d (Nmm^2)	$= (2.38\times q_{test}) + (2.04\times 10^{-11}\times EI_d) - 1.14$	$= (1.60\times 10^{10}\times q_{test}) + (0.545\times EI_d) - 8.74\times 10^9$

6.5 Point-load deflection

For fifteen specimens from the test sample, the deflection at mid-span induced by the application of a lump mass is recorded. The applied load is increased incrementally and the results, including the calculated stiffness, are recorded in Table B3 in Appendix B.

Using the resulting load-deflection slope for each specimen, the predicted bending stiffness is calculated. Calculated bending stiffness as given by Equation 12 is derived from Equation 9.

$$EI_p = \frac{(F_{app} \times L)^3}{48\,\delta} \qquad \textbf{(12)}$$

Where

EI_p is the calculated bending stiffness from the point-load deflection test,

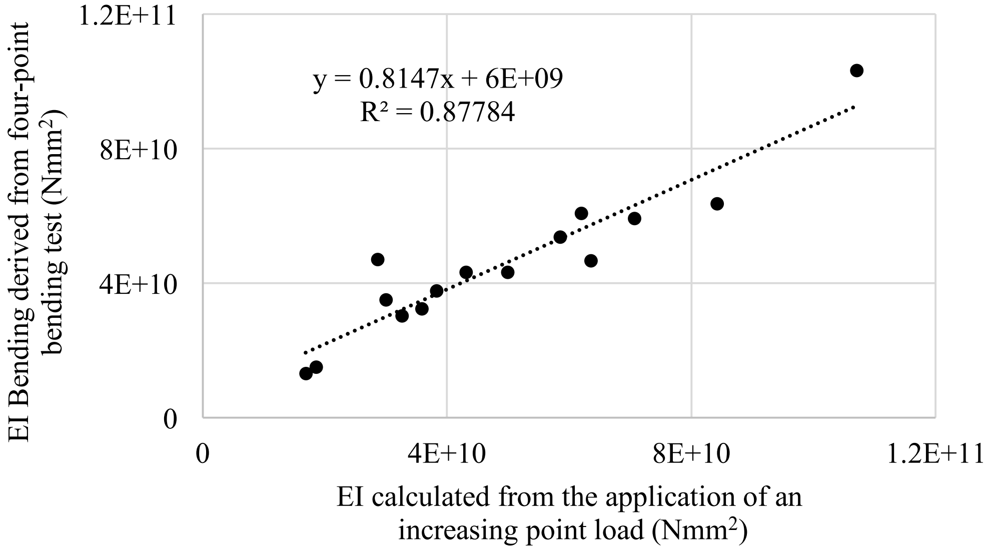
F_{app} is the applied load,

L is the length of the free span (fixed at 3300mm),

δ is the deflection at mid span resulting from load application.

Plotting the results against the bending stiffness derived experimentally from the four-point bending test which was carried out on each specimen immediately after the point-load deflection test, a strong correlation is found with $R^2 = 0.878$, as shown in Figure 26, suggesting that this method can fairly accurately predict the actual bending stiffness of a given specimen. This greatly improves the feasibility of a grading procedure where bending stiffness is required as an IP because it provides a cheap, simple and fast method of determining bending stiffness which is much easier to conduct in the field than the four-point bending test.

Figure 26: Comparison of stiffness derived from four-point bending and from the application of an increasing point load



The relevance of this test is that it would provide a simple alternative to the four-point bending test which is difficult and expensive to set up in the field. It is unlikely that users of bamboo will have access to laboratory test equipment with which to carry out a reliable bending test however as observed from the results presented in Section 6.3, EI from bending is an important indicator of bending moment capacity which is an essential property in design. Therefore, if EI can be reliably derived from this simple point-load deflection test, it would further promote the cause for a grading procedure for bamboo.

To investigate the validity of EI_p calculated from the point-load deflection test, the regressions for M_{max} previously presented in this section have been repeated using EI_p instead of $EI_{m,s}$; the results are contained in Table 14 together with the R^2 values previously reported. Figure 27 shows the simple linear correlation for EI_p against M_{max}.

Figure 27: Correlation between M_{max}, and EI_p

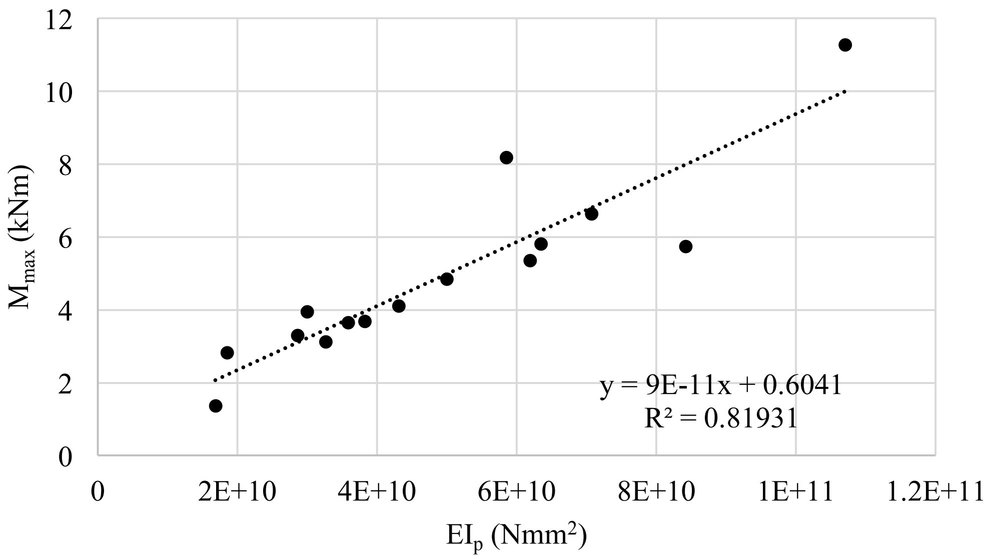


Table 14: Regression relationships for M_{max} from $EI_{m,s}$ and EI_p

Variables tested	Adjusted R^2 for M_{max}	
	using $EI_{m,s}$	using EI_p
EI	0.866	0.819
$q_{test} + D_{mean}$ + EI	0.893	0.771*
$q_{test} + D_{mean}^3$ + EI	0.892*	0.771*
D_{mean} + EI	0.864*	0.800*
q_{test} + EI	0.865*	0.789*

*The P-value for one of the variables in the combination is not significant

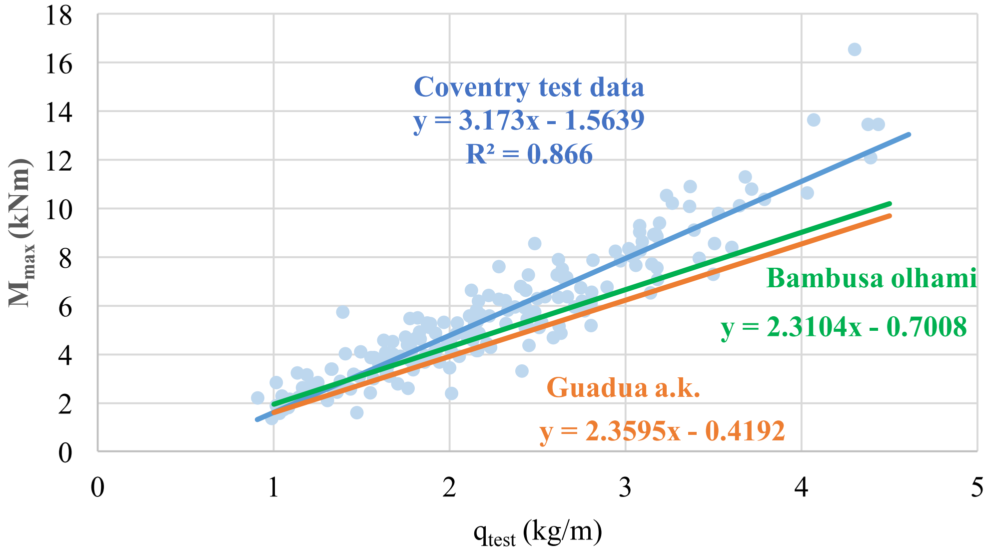
Figure 27 suggests that a positive linear relationship exists between M_{max} and EI_p with an encouraging R^2 value of 0.819. Promising R^2 values between 0.771 and 0.8 are also obtained for the multiple regressions detailed in Table 14 suggesting that it could be possible to replace the onerous four-point bending test with the cheaper and more simple point-load deflection test detailed in Section 5.5.

It should be noted however that all of the multiple regressions for M_{max} contain one or more P-value which is deemed statistically insignificant. It is likely that this is due to the limited number of observations used in the model and therefore it would be necessary to expand the data set to confirm the robustness of the multiple regressions as well as the simple linear regression shown in Figure 27.

6.6 Corroboration of results

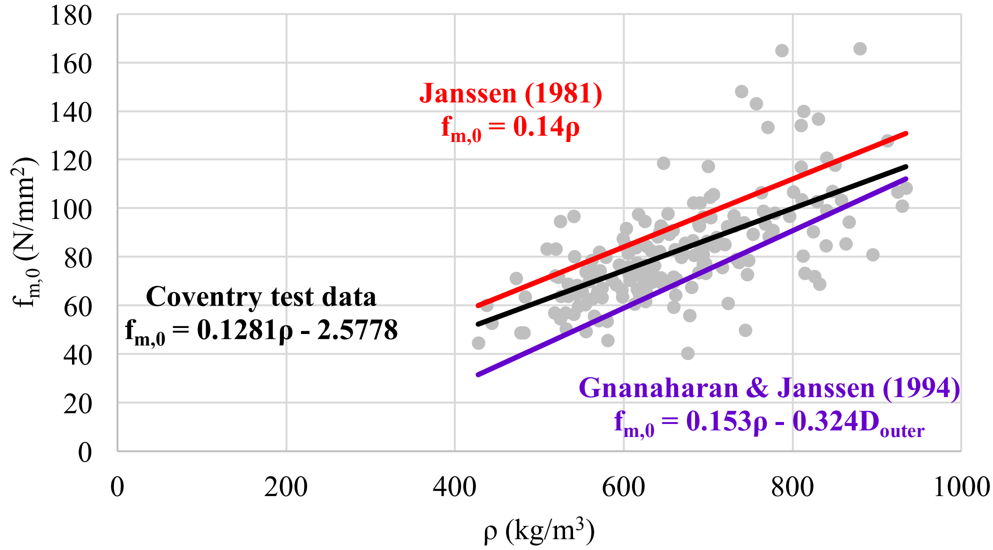
In order to corroborate the validity of the test results, data for M_{max} and q_{test} collected in Mexico for two species Guadua a.k. and Bambusa olhami have been compared with the data presented in this thesis. The relationships observed in Mexico for the two species are plotted in Figure 28 together with the data presented in this thesis and it can be seen that the relationships are close and follow a similar trend. This provides some assurance that the test data is reliable.

Figure 28: Comparison of results with data for Guadua a.k. and Bambusa olhami from Mexico



The test data collected in this investigation has also been compared with previously published work by Janssen (1981) and Gnanaharan, Janssen and Arce (1994) who established relationships between density and bending strength. The trends observed in these studies have been plotted over the experimental data shown in grey in Figure 29. It can be seen that the data collected in this investigation follows a similar trend to these studies and thereby provides further assurance that the test data collected in this investigation is reliable.

Figure 29: Comparison of experimental results for strength and density with relationships established in previously published studies



6.7 Critical analysis of results

Comparing the results of the flexural tests (from which relationships between bending stiffness and bending moment are established) with elementary beam theory suggests that the experimental findings conform to expected behaviour of flexural members.

According to Euler-Bernoulli beam theory for static beams, bending moment is directly proportional to bending stiffness as per Equation 13.

$$M = EI.k \qquad \textbf{(13)}$$

Such that:

$$k = \frac{d^2z}{dx^2} \qquad \textbf{(14)}$$

Where

z is the deflection of the beam,

x is the distance along the beam.

The constant k as given in Equation 14 therefore equates to the curvature of the beam and implies that bending moment and bending stiffness have a linear relationship, as emerges in the experimental findings. Correlating M_{max} with $EI_{m,s}$, EI_d and EI_p revealed linear relationships with a correlation coefficient of 0.866, 0.851 and 0.819 respectively, however in all cases, the correlation between bending moment and bending stiffness is not perfect as implied by static beam theory.

Considering that bamboo is a natural material with inherent variability, the imperfect relationship between bending moment and bending stiffness (illustrated by correlation coefficients of less than 1) is expected. As discussed in Section 4.2, established practice for the grading and classification of timber typically uses non-destructively measured modulus of elasticity in bending ($E_{m,s}$) to infer bending strength ($f_{m,0}$). This relationship is derived from an imperfect correlation between modulus of elasticity in bending and bending strength and therefore relies on a mean regression between the parameters.

As discussed in Johansson (2003), the strength of the relationship between modulus of elasticity and bending strength in timber established in different investigations varies due to differences in the material and test methods used, however correlation coefficients ranging between 0.51 and 0.73 are generally considered to be acceptable. In light of this, the superior correlations observed in this investigation are considered to be encouraging with respect to the potential for a grading system for bamboo which relies on non-destructively measurable stiffness to infer the bending moment capacity of a culm.

7 Potential grading methodologies

The development of a grading procedure depends on the ability to establish strong and reliable correlations between non-destructively measurable properties, which can act as IPs, and destructively measurable properties, which can be assigned as grade determining properties. This investigation aimed to establish these correlations, based on a sample of 286 specimens. Whilst it would be necessary to test many more hundreds of specimens before a robust grading procedure could be published internationally, the proposed procedure using the indicating and grade determining properties proposed in this section based on this initial sample, is considered to be a strong basis for the further development of a grading system.

As shown in Table 10 and Table 12, mass per unit length is established as a strong indicator for bending moment capacity and flexural stiffness. Flexural stiffness determined from stress waves in the dynamic test is shown to be an excellent predictor for static flexural stiffness which is well correlated to bending moment capacity.

Average external diameter is also found to be a good indicator for flexural stiffness, although not as well correlated to moment capacity compared with the other non-destructively measurable properties considered.

Regressions carried out using two variables slightly improve the observed correlations for flexural stiffness and bending moment capacity however the use of three variables does not offer any notable improvement to the resulting R^2 values and instead were proven not to be useful due to one or more variables being insignificant.

Based on these observations, it is proposed that a grading system for Guadua a.k. could be developed using mass per unit length, flexural stiffness or average external diameter as IPs. These IPs could either be used separately or in combination with one another as discussed in the following sections.

7.1 Mass per unit length as an indicating property

Previous investigations by Janssen (1981) and (1991) suggested that density could be used as a non-destructively measurable property from which strength may be inferred in a grading procedure for bamboo. However, this investigation has shown that correlations for strength properties against density are not very strong and therefore less useful than mass per unit length. Furthermore, as discussed in Section 5.1, measurement of density by the procedure contained in ISO 22175-1 (ISO 2004b) only allows for density to be determined at a single discrete location thus ignoring the variation in density along the length of a specimen (Trujillo and López 2016). The procedure used in this investigation whereby density has been estimated based on a representation of culm as a hollow cylinder is shown to be adequate for use as an approximate input value for the Timber Grader MTG for measurement of E_d, however it is not sufficiently robust as a basis for deriving correlations as it is only an approximation.

As detailed in Section 6.2, mass per unit length provides promising correlations with both bending moment capacity and flexural stiffness and has therefore been identified as an IP in the proposed grading procedure. The main advantage of using mass per unit length is that it is simple to measure and can be determined using low cost and readily available instrumentation; a tape measure, scales and a moisture meter.

The only foreseeable limitation is that the mass per unit length approach might only be applicable to dry bamboo (where moisture content is less than 20%). Unfortunately, it was not possible to procure any green bamboo to test the validity of moisture meter readings however it is expected that a moisture meter is unlikely to provide accurate readings at higher moisture contents.

7.2 Flexural stiffness as an indicating property

As demonstrated by the correlations established in this investigation, flexural stiffness is a good indicator for bending moment capacity and could therefore be used as an IP in a grading procedure. This is encouraging with regards to the potential for grading of bamboo because flexural stiffness and flexural capacity are fundamental properties in structural design.

Estimation of flexural stiffness has been investigated using three different methods, all providing promising results; from four-point bending ($EI_{m,s}$), from a dynamic stress-wave instrument such as the MTG Timber Grader (EI_d) and from a simple procedure involving the application of a point-load (EI_p). The advantage of using flexural stiffness over mass per unit length is that it is likely to be less dependent on moisture content however only dry bamboo is tested in this investigation and further work should therefore include testing of green bamboo.

If a grading procedure is to be widely adopted, it is important that the prescribed method for calculating flexural stiffness is easy to implement in the field and does involve significant costs. The dynamic technique for E_d using a handheld device such as the MTG Timber Grader is therefore considered to be less appropriate primarily due to the high cost of the equipment but also because the procedure is slow, requiring the user to obtain measurements of geometrical properties in order to input the cross-sectional dimensions and estimated density of each specimen. Whilst a four-point bending test is arguably more accurate, based on the initial investigation carried out on fifteen specimens, the point-load deflection method for the estimation of E_p presented earlier, could be the most effective in a grading procedure as the test only requires the user to have access to a lump mass and a dial gauge for measurement of deflection, which are easily accessible and relatively cheap.

Whilst grading based on EI_p is promising, significant further testing would be required to investigate the validity of the method beyond the initial fifteen tests presented. For this reason, $EI_{m,s}$ from four-point bending is considered to be the most reliable indicator at this stage in the research. Due to the destructive nature of the test, it is suggested that a grading method would be based on a machine grading system with output control to limit the number of destructive tests required.

7.3 Average external diameter as an indicating property

Whilst mass per unit length and flexural stiffness have been established as good indicators of flexural capacity and have provided stronger correlations than average external diameter, diameter is considered to be the most important potential indicating property in a grading system for full-culm round bamboo. As reported in Section 6.3, the correlations observed for average external diameter D_{mean} against flexural capacity M_{max} and flexural stiffness $EI_{m,s}$ are sufficiently strong for a grading system to be based on with R^2 values of 0.773 and 0.869 respectively.

Average external diameter is as simple to measure as mass per unit length, does not require much equipment and can be used for green as well as dry bamboo. Green bamboo has not been investigated however this is an area for further work and it is suggested that the effect of shrinkage should be explored for grading by diameter in green bamboo.

Most significantly however, are the practical implications with regard to construction; design and construction teams will be likely to specify culms by their external diameter so that structural elements fit together at connections and the structure is aesthetically pleasing. Therefore, controlling for diameter is likely to happen regardless and it would be sensible to base a grading system around this approach, with the potential for combining diameter with mass per unit length and/or flexural stiffness as IPs. Controlling for diameter would provide the basis for a visual grading procedure, even where mass per unit length and/or flexural stiffness are used as the IPs

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7.4 Combining more than one indicating property

Various combinations of mass per unit length, average external diameter and flexural stiffness as IPs are possible however based on the previous discussion, it is suggested that external diameter should be used either as an IP or a visual override in a grading procedure for full-culm round bamboo.

Two combined methods are therefore suggested; using two properties, mass per unit length with average external diameter, or all three properties, mass per unit length and flexural stiffness with average external diameter. With either method, it would be necessary to include a visual override step to eliminate any specimens exhibiting defects or splitting.

Grading by mass per unit length and external diameter would be a simple process with both properties easily measurable and with minimal equipment required. This method would only be applicable to dry bamboo until further investigation can confirm the validity of the use of a moisture meter on green bamboo.

A grading procedure based on all three properties could be either visual or machine controlled. It is proposed that grades could be stated in terms of external diameter and mass per unit length, with an associated mean and 5th percentile flexural stiffness provided for each grade as well as characteristic values for flexural and axial capacities.

7.5 Proposed grading system

Average external diameter has been identified as a fundamental property for a bamboo grading system and on this basis, the data collected during this investigation has been analysed and sorted to create a preliminary grading methodology.

To begin with, the data is sorted by diameter and separated into six 'bins'; 70-80 mm, 80-90 mm, 90-100 mm, 100-110 mm, 110-120 mm and 120-130 mm. These bins capture all of the external diameters measured in this investigation except for six specimens which fall below 70 mm or above 130 mm. The bin range 120-130 mm only contains sixteen specimens and is therefore abandoned as it does not achieve the threshold minimum requirement of twenty observations.

Analysis of the data contained in each of the bins is then carried out to determine the mean, standard deviation, coefficient of variance, 5th percentile and characteristic values. These values are presented in Table 15. Where the number of observations is below twenty, the bin is discarded from further analysis.

Characteristic values are calculated using the prescribed formula contained in ISO 22156 (ISO 2004a) given as:

$$R_k = R_{0.05}\left(1 - \frac{2.7\frac{s}{m}}{\sqrt{n}}\right) \qquad \textbf{(15)}$$

Where

R_k and $R_{0.05}$	are the characteristic and 5th percentile values respectively
s	is the standard deviation
m	is the mean
n	is the number of observations

Table 16 summarises the key properties for each bin range or 'grade'. These are the mean and 5th percentile flexural stiffness, together with characteristic values for flexural capacity, density and mass per unit length for each diameter range (or grade).

Extending the analysis to consider a combined method approach, mass per unit length is introduced as an IP with the diameter ranges still referred to as the grades, as shown in Table 17. Using the characteristic and mean values for mass per unit length as calculated in Table 15, values for flexural stiffness and moment capacity are derived using the equations which were established earlier in this investigation. Flexural stiffness and moment capacity are therefore referred to as 'secondary properties' which are properties inferred from an equation requiring an experimentally measured input. The equations are summarised in Table 18.

Table 15: Preliminary analysis of data for grading based on average external diameter

Bin range	**70-80 mm**	**80-90 mm**	**90-100 mm**	**100-110 mm**	**110-120 mm**
Size of bin	26	51	63	72	52
Flexural stiffness, $EI_{m,s}$ ($GNmm^2$)					
n	20	39	49	68	44
Mean	22.5	32.9	49.8	69.6	96.0
Std Dev	8.22	8.68	15.1	14.9	15.5
CoV	0.365	0.264	0.303	0.214	0.161
5^{th} percentile	13.1	21.9	32.7	46.8	68.7
Characteristic	10.2	19.4	28.9	43.5	64.2
Flexural capacity, M_{max} (kNm)					
n	18	28	44	52	26
Mean		3.27	4.62	5.98	8.43
Std Dev		1.05	1.23	1.27	1.95
CoV		0.320	0.265	0.212	0.231
5^{th} percentile		1.76	3.12	4.23	5.41
Characteristic		1.47	2.79	3.90	4.75
Density, ρ (kg/m^3)					
n	26	51	63	72	52
Mean	678	699	701	671	657
Std Dev	104	102	96.3	118	95.1
CoV	0.153	0.146	0.137	0.175	0.145
5^{th} percentile	519	526	547	506	528
Characteristic	477	497	521	477	500
Mass per unit length, q_{test} (kg/m)					
n	26	51	63	72	52
Mean	1.22	1.56	1.97	2.46	3.07
Std Dev	0.223	0.311	0.322	0.381	0.468
CoV	0.183	0.199	0.163	0.155	0.152
5^{th} percentile	0.979	1.18	1.57	1.92	2.33
Characteristic	0.884	1.09	1.48	1.83	2.19

Table 16: Summary of key properties for each grade

Grade (Diameter, mm)	**EI_{mean} ($GNmm^2$)**	**$EI_{0.05}$ ($GNmm^2$)**	**$M_{0,k}$ (kNm)**	**ρ_k (kg/m^3)**	**q_k (kg/m)**	**t_k (mm)**
70-80	22.5	13.1	*	477	0.88	5.86
80-90	32.9	21.9	1.47	497	1.09	7.90
90-100	49.8	32.7	2.79	521	1.48	7.92
100-110	69.6	46.8	3.90	477	1.83	9.84
110-120	96.0	68.7	4.75	500	2.19	11.9

*sample too small (n > 20)

Table 17: Grade determining properties inferred from mass per unit length in a combined method approach

Grade	**Grade determining properties**				
	Indicating properties		**Secondary properties (q_k or q_{mean})**		
Diameter (mm)	q_k (kg/m)	q_{mean} (kg/m)	EI_{mean} ($GNmm^2$)	$M_{0,k}$ (kNm)	t_k (mm)
70-80	0.88	1.22	22.3	1.24	6.98
80-90	1.09	1.56	35.3	1.90	7.78
90-100	1.48	1.97	51.0	3.12	9.27
100-110	1.83	2.46	69.9	4.23	10.6
110-120	2.19	3.07	93.4	5.40	12.0

Table 18: Summary of equations for established relationships for the calculation of grade determining properties

Characteristic property	Equation
Mean flexural stiffness	$= 38.4\ q_{mean} - 24.7$
Minimum flexural stiffness	$= 0.7\ EI_{mean}$
Characteristic bending capacity parallel to fibres	$= 3.17\ q_k - 1.56$

7.6 Assumptions and limitations

The proposed grading system is based on assumptions underpinning the calculation of the characteristic and secondary properties detailed in Section 7.5. Characteristic values are calculated from Equation 15 taken from ISO 22156 (ISO 2004a) and the proposed grading methodology therefore relies on the assumption that the sample mean and standard deviation are representative of the population.

The application of the proposed grading system is limited by the scope of the investigation as detailed in Section 1.2. The grading system therefore applies only to samples of bamboo which satisfy the following criteria:

1. Full-culm round bamboo, specifically of the Guadua a.k. species;
2. Dry samples (moisture content below 20%);
3. Samples with an average external diameter (calculated as per Figure 3) greater than 70 mm and less than 130 mm.

It should be noted that the proposed grading system applies only to dry bamboo however it may be possible to include green samples following further testing. The sample considered for this investigation did not include any green samples and consequently, the effects of shrinkage (occurring as a result of the drying process) are unknown.

A further limitation of the proposed grading system is that only characteristic flexural properties can be determined using the prescribed indicating and grade determining properties. The scope of the investigation was limited such that only flexural testing was undertaken and therefore the grading system does not include any classification of samples with respect to shear and compressive strength. Only one configuration was trialled for the static bending test (as per Section 5.4) and the proposed grading system is only applicable to bamboo tested using the same method.

As referred to above, the validity of the proposed grading system is limited by the representativeness of the sample considered in the investigation. As detailed in Table 2, the sample contains specimens from a range of positions along the culm of the plant however, all specimens originated from one of two plantations in Colombia and the proposed grading system therefore can only be used to grade bamboo culms originating from one of these plantations.

8 Conclusions

The bamboo supply chain currently relies on experience whereas structural design using mainstream construction materials is based on standardised procedures and verifiable material strength properties. Mechanical properties of factory-made materials can be controlled however for natural materials with inherent variability, grading can provide a method for estimating the mechanical properties of members.

Current bamboo design codes only contain guidance on visual inspection, limiting the safe and economical use of full-culm bamboo. This thesis addresses this limitation by presenting the findings of an investigation into the flexural properties of round full-culm bamboo demonstrating that grading is possible. The findings suggest that the extant stress-based approach for bamboo design should be replaced with a capacity-based approach similarly to that for engineered timber products.

Experimental tests were carried out on 286 specimens of Guadua a.k. to establish physical and mechanical properties, measured both destructively and non-destructively. Analysis of the data set demonstrated that relationships exist between destructively and non-destructively measurable properties. The strongest relationships were established when the effect of geometric uncertainties is removed and overall section properties such as flexural stiffness, flexural capacity and mass per unit length were considered instead. For simple linear regressions, mass per unit length, flexural stiffness and average external diameter provided R^2 values ranging between 0.77 and 0.87 for flexural capacity, and between 0.87 and 0.93 for flexural stiffness. Multiple regressions using two variables provided slightly stronger R^2 values for both flexural capacity and flexural stiffness however the use of three variables did not offer any significant improvement.

This investigation also revealed that dynamic methods of establishing modulus of elasticity can successfully be used to determine the mechanical properties of a bamboo culm. A Brookhuis Timber Grader MTG was trialled, confirming the validity of the use of handheld non-destructive instruments in a bamboo grading procedure. However, it is noted that the high cost of such instruments limits their appropriateness for a grading system in bamboo growing regions.

Conversely, a simple point-load deflection test was found to provide a cheap, simple and fast method of estimating the flexural stiffness of a culm. The proposed test is much easier to conduct in the field than the four-point bending test and does not require specialist laboratory equipment. However, the reliability of this approach is unknown due to the small sample size investigated.

Based on the observed correlations, mass per unit length, average external diameter and flexural stiffness were identified as potential Indicating Properties (IPs) for flexural stiffness and flexural capacity in a grading system for bamboo. Two simple grading systems are presented; using diameter alone as an indicator and a combined method using diameter together with mass per unit length as IPs.

Grading by external diameter would improve the reliability of structural design using bamboo which currently relies on visual inspection to either accept or reject a member. Grading by diameter also lends itself well to a system which infers overall member capacity rather than a stress-based approach which seeks to estimate strength properties. Using the proposed grading system, external diameter (and mass per unit length) can be used to infer either the flexural capacity or flexural stiffness of a bamboo culm; flexural stiffness can also be used to infer flexural capacity.

As discussed in Section 3, bamboo is a fast growing and renewable resource which can be procured at a low cost. The potential for carbon off-setting (Kuehl and Yiping, 2012) and its potential to outperform materials such as concrete, steel and wood over its lifecycle make bamboo an attractive option for sustainable construction, particularly in regions where the plant grows in abundance. Grading of bamboo, as proposed in this thesis, can thereby simplify the design process and promote wider acceptance of the material.

The conclusiveness of the experimental findings and the proposed grading system is limited as discussed in Section 7.6 and further work is required to corroborate the relationships established and the validity of the grading system. Recommendations for future efforts in this area are provided in Section 9.

9 Recommendations for future work

Although this investigation successfully establishes strong relationships and confirms that grading is possible, further work is advised to confirm the findings and extend the analysis. Only Guadua a.k. has been tested and it is therefore recommended that other species should be added to the data set; furthermore, only dry bamboo is considered here and it is unknown whether the findings of this investigation would extend to green bamboo. In particular, it is expected that moisture meter readings are unlikely to provide accurate readings at higher moisture contents, compromising the simplicity of using mass per unit length as an IP for grading. Average external diameter is likely to be susceptible to the effects of shrinkage and it may therefore be necessary to use flexural stiffness as an indicator of flexural capacity in green bamboo.

Another area requiring significant further investigation is the validity of the point-load deflection test proposed in this thesis as an approximation for flexural stiffness from four-point bending. Based on the initial investigation, flexural stiffness approximated from the application of a lump mass and measurement of the associated deflection provided positive linear correlations with flexural stiffness and flexural capacity from four-point bending with R^2 values of 0.88 and 0.82 respectively. The method could therefore provide a much quicker and cheaper alternative to the four-point bending test as prescribed in ISO 22157-1 (ISO 2004b) however, only fifteen specimens were tested and the validity of the method must be rigorously explored with an expanded data set.

Lastly, it is recommended that other destructively measured strength properties such as shear capacity and compression capacity should be investigated with respect to the proposed grading system with the aim of formulating a holistic approach to building with bamboo.

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11 Appendix A: Assumptions for environmental impact assessment

Input	Amount
Bamboo per shipment (linear metres)	2700 m
Average weight per culm	14 kg
Mass per unit length of culm	2.7 kg/m
Mass in one shipment	7290 kg
Charcoal volume per shovel	0.0135 m^3
Specific energy of charcoal	30000 kJ/kg
Density of charcoal	208 kg/m^3
Specific energy of bamboo/hardwood	19000 kJ/kg
Specific heat capacity of water	4.2 kJ/kg°C
Diesel consumption - medium sized lorry	0.094 l/km (based on a vehicle efficiency of 30 mpg)
Diesel consumption - articulated lorry	0.353 l/km (based on a vehicle efficiency of 8 mpg)
Diesel consumption - sea vessel	200 tonnes per day
Diesel conversion	1150 l/tonne
Sea vessel speed	46 km/hour
Sea vessel size	5000 TEU (average sea cargo ship)
Energy consumption - sea vessel	0.37 kJ/kg/km (average sea cargo ship)
Energy density - diesel	34000 kJ/l
CO_2 emissions from diesel	3.0648 $kgCO_2/l$
CO_2 emissions from coal	3.1509 $kgCO_2/kg$
CO_2 emissions from bamboo/hardwood	0.1649 $kgCO_2/kg$

12 Appendix B: Results from experimental programme

Table B1: Summary of physical properties for all specimens

Sample ID	Average diameter (D_{mean})	Average wall thickness (t_{mean})	Total Length (l_{sp})	Total Mass	Average moisture content	Density (ρ)	Mass per unit length (q_{test})	Mass per unit length at 12% moisture content
	(mm)	(mm)	(mm)	(kg)	(%)	(kg/m^3)	(kg/m)	(kg/m)
I73	87.00	16.38	4092	10.59	12.40	712.3127087	2.58797654	2.578766659
S37	98.75	10.75	4035	8.1	11.05	675.4612988	2.007434944	2.024607958
M43	92.00	8.50	3979	7.94	12.50	894.93458	1.99547625	1.986607467
M13	98.00	8.25	4035	8.1	12.20	862.9849091	2.007434944	2.003856629
I8	83.00	11.00	3875	6.94	15.20	719.801437	1.790967742	1.741218638
M93	95.50	9.63	4085	7.78	9.80	733.4494296	1.904528764	1.942688721
M25	95.00	8.88	4084	7.17	12.20	731.1154355	1.755631734	1.752502265
M30	88.25	9.88	4126	7.26	13.50	723.6738276	1.759573437	1.736319162
M72	100.00	10.25	3900	7.37	11.10	653.8749284	1.88974359	1.905052044
M18	96.75	9.63	4129	6.92	11.75	636.1621258	1.675950593	1.679699924
M5	99.00	8.25	4144	6.72	12.80	689.444119	1.621621622	1.610120759
M70	97.50	9.00	3955	7.23	11.55	730.5604488	1.82806574	1.835440276
M78	110.75	9.88	4129	9.92	11.10	767.7083505	2.40251877	2.421981118
M64	107.75	10.13	4025	10.72	9.85	857.675391	2.663354037	2.715481586
M82	105.75	12.50	4155	7.98	11.85	524.4730018	1.920577617	1.923153269
I18	103.25	16.88	3916	6.94	13.10	525.3231081	1.772216547	1.754980135
I38	105.75	17.75	4045	9.58	13.60	482.6319637	2.368355995	2.334998868

M85	105.00	11.25	4121	10.28	10.45	752.8645162	2.49454016	2.529547288
I2	106.25	17.38	4044	11.09	12.45	565.2832273	2.742334322	2.731360108
I15	108.75	18.63	4075	11.42	12.35	531.4312135	2.802453988	2.793723601
I10	109.75	19.00	4116	11.9	14.30	533.7298446	2.891156463	2.832979211
S32	97.00	12.38	4295	9.07	10.70	641.8748462	2.111757858	2.136557182
M68	96.75	9.38	3911	6.93	11.50	688.5525338	1.771925339	1.779871192
I44	102.00	18.75	4048	9.37	12.45	472.0235862	2.31472332	2.30546031
I93	108.00	13.00	4112	9.98	11.70	625.5479497	2.427042802	2.433561269
I35	107.50	17.63	4083	11.43	11.90	562.5342228	2.799412197	2.801913906
I25	109.00	19.50	4046	10.59	12.20	477.3781777	2.617399901	2.612734304
M11	105.00	11.38	4211	9.05	11.40	642.3477823	2.149133223	2.160708446
I27	106.00	16.38	4075	10.71	12.10	570.0349812	2.628220859	2.625876326
M100	107.75	12.00	4103	10.04	11.35	677.8947874	2.446990007	2.461274188
I11	111.00	16.63	3985	12.66	12.05	644.5207275	3.176913425	3.175495793
I42	104.00	14.50	4018	9.8	11.75	598.2397041	2.43902439	2.444480821
M27	99.50	10.50	4001	7.2	11.95	612.9637148	1.799550112	1.800353842
M10	102.25	12.38	4001	8.02	11.50	573.6828053	2.004498875	2.013487659
I4	104.00	15.50	4213	12.5	12.15	688.4837787	2.967006883	2.963038528
I7	112.25	19.88	4060	12.89	12.65	550.44689	3.174876847	3.15655754
I21	102.50	14.75	4150	10.97	12.30	650.0840531	2.643373494	2.636311944
M34	91.50	11.00	4074	8	9.70	705.8794264	1.963672067	2.004842949
M14	111.50	13.38	4123	11.59	11.55	681.7839419	2.811059908	2.822399907
M49	89.50	9.50	3850	5.74	10.20	624.4356619	1.490909091	1.515261508
I52	94.25	13.25	4020	8.97	12.25	661.7830204	2.231343284	2.226373699
I60	104.00	13.25	4063	10.59	11.40	689.9803985	2.606448437	2.620486759
I46	98.50	13.00	3965	8.55	11.15	617.5378527	2.156368222	2.172858667
I13	104.75	16.13	3880	10.73	11.10	615.9736752	2.765463918	2.787866416
M8	83.50	8.63	3840	4.72	10.05	605.849791	1.229166667	1.250946539

I77	108.75	18.13	4079	11.44	10.90	543.4960745	2.804608973	2.832427457
M47	113.50	11.38	4010	9.95	11.60	679.9005	2.481296758	2.490190295
M36	108.00	12.38	4159	10.17	11.05	657.7570385	2.445299351	2.466218166
I43	93.00	14.63	4069	8.83	11.20	602.6285633	2.170066355	2.185678344
I6	112.00	16.38	4040	12.88	10.40	648.0848487	3.188118812	3.234323432
M63	116.00	13.50	4021	12.12	10.40	693.3636027	3.014175578	3.057859282
M79	109.25	13.38	4051	8.66	8.90	530.6480938	2.137743767	2.198597814
I69	113.75	19.13	4063	12.32	11.35	533.3430946	3.032242186	3.049942746
S65	84.50	14.75	4179	5.99	10.10	443.4741871	1.433357263	1.458092765
M38	100.25	11.13	4103	7.87	9.80	615.7774491	1.918108701	1.956540751
I54	112.25	18.25	3990	12.27	13.45	570.5990864	3.07518797	3.035884113
S16	94.50	10.25	5220	9.77	10.80	689.8908947	1.87164751	1.89191806
I1	102.75	15.50	3934	9.59	14.00	573.7692179	2.43772242	2.39495536
M33	92.00	9.00	4219	6.27	11.45	633.267997	1.486134155	1.49346815
M41	109.00	10.88	3980	8.79	11.10	658.789995	2.208542714	2.226433699
I39	103.00	17.00	4115	10.31	10.55	545.4960126	2.505467801	2.53833011
M55	103.25	11.63	4077	7.69	11.65	563.6750428	1.886190827	1.89210365
S34	74.75	11.50	4339	5.04	11.25	508.3146697	1.161557963	1.169388691
M28	107.00	11.75	4114	9.53	11.25	658.8338274	2.316480311	2.332097032
M48	98.75	10.88	4015	7.46	9.00	618.8833537	1.858032379	1.909170884
S62	83.00	8.50	4225	5.27	9.60	626.9874252	1.247337278	1.274651233
S92	100.50	13.25	5361	10.99	10.40	564.4437891	2.049990673	2.079700683
S63	98.25	12.00	5156	11.44	10.65	682.3746637	2.218774244	2.245844693
S55	88.25	7.75	5175	8.12	9.20	800.5679869	1.569082126	1.609315001
S78	96.25	9.00	4979	9.12	11.30	742.4973266	1.831693111	1.843213194
S70	78.75	10.25	5119	6.95	11.15	615.5103576	1.357687048	1.36806972
S56	99.00	9.25	5243	10.07	10.30	736.416567	1.920656113	1.950258247
S46	70.75	7.75	3872	4.39	10.20	739.1576005	1.133780992	1.1523001

I12	105.25	17.25	3708	9.88	11.30	558.721746	2.664509169	2.681267089
M57	93.00	10.88	4235	7.64	10.05	642.9621729	1.804014168	1.835979889
S47	83.18	6.70	5220	6.34	12.93	754.2452328	1.214559387	1.204521706
S38	85.02	9.19	5190	7.97	12.90	701.7282063	1.535645472	1.523853747
S5	74.94	7.06	5270	4.78	13.70	602.2365566	0.907020873	0.893459435
S21	87.80	7.16	4965	6.98	12.60	775.0375704	1.405840886	1.398349727
S54	90.77	7.94	5176	8.5	12.70	794.5898419	1.642194745	1.632477616
S26	88.82	10.25	5175	9.5	11.70	725.4757349	1.835748792	1.841228639
S97	92.93	9.88	5174	9.68	12.10	725.5921916	1.870892926	0.159954204
4S	98.52	10.82	5201	12.74	11.10	821.6859242	2.449528937	2.470113214
S11	103.22	8.96	5099	11.5	11.80	850.1241303	2.255344185	2.258705354
S23	101.22	10.62	5423	13.23	10.70	807.1658538	2.439609072	2.468258502
4M	101.76	10.87	5450	11.86	11.97	701.0688103	2.176146789	0.18791707
S50	74.27	8.54	5069	5.56	13.10	621.7965109	1.096863287	1.08651552
S36	94.71	9.65	5075	9.85	11.20	752.766461	1.9408867	1.954264103
S51	98.99	10.03	5137	11.1	13.60	770.868036	2.160794238	2.129735594
S88	104.19	10.69	5180	11.96	11.30	735.2395658	2.308880309	2.322705939
S13	81.41	9.56	4933	5.67	12.90	532.7467026	1.149401987	1.140239349
S59	73.25	7.92	5110	5.29	11.80	637.0900004	1.035225049	1.036767858
S1	78.78	7.35	5094	6.41	11.40	763.4432611	1.258343149	1.265499246
S45	94.66	9.61	5134	9.03	14.30	684.7933807	1.758862485	1.723972564
S87	79.43	10.81	5195	8.55	13.77	706.174413	1.645813282	0.124801007
M58	118.39	10.42	4085	11.64	9.67	806.2826235	2.849449204	0.299098698
S85	88.16	9.37	5324	10.33	13.00	836.2474858	1.940270473	1.922532819
S10	82.39	7.33	5155	6.84	14.70	768.1003761	1.326867119	1.296009744
I83	117.84	19.80	4162	16.98	9.90	669.1382472	4.079769342	4.157726718
M96	119.31	12.97	4036	11.22	10.60	641.5170981	2.779980178	2.816018511
I14	118.64	19.20	3976	14.69	11.00	616.0061394	3.694668008	3.727953305

M56	99.81	10.14	5069	9.93	10.70	686.0163075	1.958966266	1.981971289
M91	118.16	11.91	4230	13.77	10.40	818.8859841	3.255319149	3.301500857
I82	114.92	10.77	4100	9.88	12.00	683.7206762	2.409756098	0.207609756
S93	75.93	8.45	4226	5.97	10.20	788.9179289	1.412683389	1.435758072
S82	80.86	10.50	4119	5.78	11.30	604.5030775	1.403253217	0.127775903
M40	114.35	13.51	4055	12.99	10.70	748.6011508	3.203452528	3.242048341
M65	111.89	10.34	4126	10.27	10.90	754.3092646	2.489093553	2.513027145
S64	92.12	9.47	5016	9.33	12.20	756.2981626	1.860047847	1.856180804
S44	86.22	7.46	4063	4.93	11.40	657.7146871	1.213389121	1.219559512
S8	68.16	6.81	3935	3.59	11.70	694.7453105	0.912325286	0.080457033
M87	94.23	9.38	4083	6.37	12.60	623.9398137	1.560127357	1.552273592
M62	98.13	8.50	4086	6.87	11.10	702.5227742	1.681350954	1.695479954
M29	98.78	8.90	3984	7.9	11.10	788.8728383	1.982931727	0.183544094
M53	88.89	7.24	4019	6.21	12.10	832.1926982	1.54516049	0.13210532
I24	117.64	22.61	3967	13.98	11.60	522.040365	3.52407361	0.31325099
I49	98.93	19.57	4047	8.64	12.40	437.4974151	2.13491475	0.17844064
I55	111.16	16.73	3904	10.73	12.90	553.9268624	2.74846311	0.22145890
M45	86.61	10.13	4057	8.73	11.80	778.9229655	2.15183633	0.18828568
I22	113.11	16.03	4014	12.27	12.30	625.1936748	3.05680120	0.25741484
I50	99.62	16.41	4091	9.1	11.90	518.6138433	2.22439501	0.19312577
I9	112.34	17.65	4023	12.78	11.70	604.9646435	3.17673378	0.28015290
M94	121.26	12.64	4264	14.93	10.70	812.0069253	3.50140713	0.33517743
I84	134.20	20.07	4161	18.44	10.70	615.9277235	4.43162701	0.42422412
I37	109.86	17.67	3865	11.95	10.80	604.0692505	3.09184994	0.29346372
M99	112.36	10.17	4079	8.32	11.00	624.9885965	2.03971562	0.19037346
I87	106.24	19.22	4159	13.05	10.30	597.1848579	3.13777350	0.31100056
I45	120.52	19.62	4441	14.94	11.10	540.9982805	3.36410718	0.31138843
S90	107.77	8.60	4755	10.83	10.50	849.6996532	2.277602524	2.308520205

I76	110.36	17.40	4079	11.99	11.40	578.3856834	2.939445943	2.955277788
I36	126.04	21.74	4077	17.83	11.30	614.040526	4.373313711	4.400818829
M76	106.55	10.98	4232	8.98	10.70	643.9369252	2.121928166	2.146846925
I70	108.61	11.44	3841	9.31	10.70	694.0782697	2.423847956	2.452312295
I34	100.08	12.54	4126	8.64	11.60	607.2847188	2.094037809	2.101543321
I67	109.8325	17.8375	4044	13.59	10.70	651.8688482	3.360534125	3.399998392
M83	116.655	13.0025	4115	13.29	9.80	762.7788189	3.229647631	3.294358239
M66	119.6675	13.84875	4083	12.94	10.30	688.3856703	3.169238305	3.218084226
S40	96.9175	10.5525	5016	12.17	9.90	847.4030827	2.426236045	2.472597243
S99	88.6875	9.5325	5031	7.3	11.60	612.1156777	1.451003777	1.456204507
M6	105.045	10.62	4012	9.13	10.40	722.3513192	2.275672981	2.308653749
I57	125.2675	15.80125	4076	13.8	10.00	623.0506499	3.385672228	3.447229905
M92	108.3975	11.2925	4198	11.07	9.50	765.4619759	2.636969986	2.69717478
I20	121.97	19.6575	3908	13.35	11.80	540.6545433	3.416069601	3.422180638
I19	111.3075	16.76875	4068	8.66	11.90	427.4413466	2.128810226	2.130712648
I80	131.91	18.27375	4074	16.42	10.70	617.8139109	4.030436917	4.077768155
I88	132.1675	19.20125	4270	18.74	11.20	644.0411613	4.388758782	4.420332586
I35	123.42	18.65	4190	18.01	9.90	700.2192357	4.298329356	4.380463038
M84	123.9375	12.24875	4171	12.85	10.30	716.8228884	3.080795972	3.128278775
I66	119.81	21.27875	4002	16.27	10.00	617.2207122	4.065467266	4.139384853
I79	116.4375	17.0225	4005	12.65	10.70	594.1045421	3.15855181	3.195644108
I3	119.7725	17.97375	4084	14.71	10.30	626.6079846	3.601860921	3.657374643
I32	119.595	18.0025	4075	14.99	9.80	640.2206528	3.678527607	3.752232168
I56	115.815	17.67375	4106	13.4	11.30	598.901896	3.263516805	3.284042068
I16	119.455	20.8225	3964	14.44	11.10	564.5868555	3.642785066	3.672294576
I17	116.165	17.70375	4041	12.44	10.90	562.1484843	3.078445929	3.10898056
I64	121.165	18.85	4112	15.56	10.60	624.5338048	3.784046693	3.831946018
I89	121.7075	16.02375	4119	15.3	10.30	698.196055	3.714493809	3.771743487

S33	80.57	8.76375	5217	7.67	14.10	743.6565845	1.470193598	1.44313482
S96	102.4725	8.9875	4996	10.74	12.40	814.4250875	2.149719776	2.142069528
S75	90.1775	7.975	5143	8.75	13.10	826.0872866	1.701341629	1.68479454
S68	76.46	10.06	4900	5.88	16.70	571.8278633	1.2	0.075932203
S86	82.575	9.13	5184	8.48	15.60	776.5116467	1.635802469	0.110367396
S9	89.05	8.90875	5080	7.94	17.43	696.8415428	1.562992126	0.09496661
S25	75.78	11.4725	5114	5.57	16.50	632.4109462	1.089166993	0.069706688
S95	95.59	10.08625	5247	13.22	15.83	929.9414964	2.519534972	0.167636386
S91	85.44	10.03625	4680	7.75	17.53	696.5327817	1.655982906	0.100073787
S12	81.265	8.86125	5214	6.32	14.27	601.3677432	1.212121212	0.088924176
S28	83.6875	9.7625	5285	8.42	17.90	702.6917377	1.593188269	0.094411157
S24	79.8225	9.2075	5252	9.01	15.30	839.8689195	1.715536938	0.117877385
S49	75.72	7.23	5035	5.18	16.37	661.3250123	1.028798411	0.066348612
S17	87.9925	8.80375	5110	7.87	17.17	703.1901367	1.540117417	0.094950358
S35	96.88	9.34875	5150	9.19	15.00	694.1314674	1.784466019	0.124912621
S20	94.5375	33.51125	5270	8.66	15.10	568.7190783	1.643263757	0.114314
S69	96.625	9.3425	5137	7.96	14.60	604.8718114	1.549542535	0.111249208
S76	87.85	8.47875	5029	8.21	18.57	772.1765326	1.632531318	0.093446426
S57	75.5325	7.005	4979	5.21	18.43	693.8613494	1.046394858	0.060306805
S7	82.73	9.3475	5190	7.08	19.40	633.0354775	1.36416185	0.07489516
S27	79.62	8.21	5100	6.32	15.40	672.8137205	1.239215686	0.084629364
S60	79.2325	11.8925	5184	6.75	14.70	517.5384671	1.302083333	0.092887473
S83	88.28	10.66625	5250	11.34	14.63	830.52642	2.16	0.154746269
S39	107.2275	10.43125	5180	13.54	14.13	824.0321293	2.613899614	0.193451601
S3	80.475	10.37	5120	6.85	17.07	585.791395	1.337890625	0.082939345
S48	79.4975	20.015	5100	6.06	15.50	524.4976105	1.188235294	0.080655971
S74	103.6275	10.9675	5120	11.09	16.23	839.3565434	2.166015625	0.140770068
S42	84.6975	7.4975	4960	5.23	14.80	579.8776429	1.054435484	0.074744794

S15	83.4625	11.2725	5075	6.74	15.77	519.4894013	1.328078818	0.088714609
S53	83.0275	9.76875	4860	5.26	15.33	481.3944763	1.082304527	0.074215168
S6	98.9375	10.835	5245	8.56	15.87	544.2034011	1.632030505	0.108371986
45	75.755	7.64375	4009	5.31	11.40	809.8102456	1.32451983	0.119634049
75	76.9375	8.2425	4011	3.96	12.10	555.0199163	0.987284966	0.084409096
41	92.2975	11.02875	4010	7.44	12.00	658.9141259	1.855361596	0.159846538
36	107.9975	11.27625	4010	9.75	14.50	709.6166124	2.431421446	0.175689808
31	89.345	8.78375	4009	7.78	14.50	658.9141259	1.940633574	0.140226426
78	91.8	15.16	4010	8.65	17.57	590.9723539	2.157107232	0.130123524
F	73.5325	6.7025	4007	4.57	11.33	810.4732795	1.140504118	0.103570104
10	75.785	5.98875	4002	4.05	10.87	770.6546315	1.011994003	0.095514041
54	99.8425	14.2725	4010	9.95	17.27	646.7065383	2.481296758	0.152137903
73	99.74	10.64	4009	8.16	14.50	683.4156154	2.035420304	0.147075532
16	89.985	8.405	4006	6.99	12.70	810.0185028	1.744882676	0.142647343
53	94.0225	13.13625	4011	8.41	15.57	628.1268449	2.096733982	0.14175103
47	91.34	9.73125	4019	7.98	13.37	795.8471342	1.985568549	0.154791423
71	103.8575	9.69875	4009	10.49	14.23	912.0383704	2.616612622	0.192381147
77	87.42	7.7475	4008	6.44	13.63	828.587261	1.606786427	0.122979553
1	75.8	10.84375	4013	6.72	13.03	756.7454171	1.674557688	0.133646409
E	90.16	7.40125	4003	6.47	12.20	839.9430122	1.616287784	0.13713957
77A	98.5325	15.47	4009	10.85	17.37	670.4223704	2.706410576	0.165037015
76	73.155	7.41375	4007	4.05	11.30	660.1002748	1.01073122	0.092034062
H	74.4925	7.595	4010	5.63	12.87	879.5823035	1.403990025	0.113399194
31A	96.56	8.80375	4008	8.24	11.70	847.0398994	2.055888224	0.181306678
67	83.5	8.72	4003	6.41	9.67	781.6649184	1.601299026	0.168136398
I	100.5675	8.9375	4005	7.7	9.27	747.2821192	1.922596754	0.209737828
62	67.235	5.7725	4006	3.63	8.90	812.9646179	0.906140789	0.102512897
12	101.8325	8.49625	4010	9.33	9.57	933.9201966	2.326683292	0.24661375

4	99.57	16.745	4016	12.29	10.40	702.3631366	3.060258964	0.300657021
38	91.075	8.995	4008	6.58	9.27	707.7987521	1.641716567	0.179096353
43	91.1725	6.645	4002	5.56	11.13	787.3264196	1.389305347	0.128243571
16A	97.1275	16.3225	4009	9.65	9.60	580.9201924	2.407084061	0.25433341
74	100.14	7.9975	4009	8.58	9.97	924.457859	2.140184585	0.218572043
72	103.485	16.79875	4007	10.18	12.03	555.3303125	2.54055403	0.21831871
73A	96.555	9.32625	4007	7.19	10.00	702.0903005	1.79435987	0.18269846
6	109.3875	16.05625	4003	12.59	12.10	668.0655286	3.145141144	0.268897563
75A	91.08	13.8525	4009	7.28	12.10	540.3128738	1.815914193	0.155253733
80	89.8225	9.6025	4006	5.51	10.43	568.3603954	1.375436845	0.134736671
7	93.74	8.2275	4010	7.68	9.53	866.5018221	1.91521197	0.203642792
89	112.1875	15.4175	4002	13.99	11.33	745.8234932	3.495752124	0.317452085
I85	108.75	14.125	4236	13.55	11.75	761.7967615	3.198772427	3.205928517
M20	99.25	8.75	4053	7.09	11.00	703.1745218	1.74932149	1.765081143
M86	107.5	11.375	4127	9.82	10.30	692.6907498	2.379452387	2.416125724
I72	110	13.125	4265	10.95	12.00	642.7383054	2.567409144	2.567409144
I31	100.75	16.375	3891	7.61	11.70	450.5867937	1.955795425	1.961048233
M61	103.25	9.125	3964	7.83	11.75	732.0493869	1.975277497	1.979696463
M32	111.25	10.25	4088	11.03	12.40	829.601471	2.6981409	2.688538975
M89	112.75	10.75	4171	11.59	9.80	806.6492557	2.778710141	2.834385572
S91	109.5	12.625	4094	10.84	10.00	689.1098678	2.647777235	2.695918639
I51	99.5	16.625	4093	11.62	13.00	655.8874414	2.838993403	2.813869568
M60	99.25	9.125	4060	7.47	11.60	712.1419094	1.839901478	1.846496107
S18	84.5	8.875	4208	5.66	10.65	637.9065742	1.345057034	1.361467581
M81	114.25	11.125	4160	12.24	10.20	816.3459327	2.942307692	2.990367165
M9	107.5	12.625	4061	9.08	9.55	594.182437	2.235902487	2.285906696
M22	106.75	10.25	4124	9.77	8.65	762.3859001	2.369059166	2.442104248
M73	84	9.75	4067	8.21	8.60	887.6015221	2.018686993	2.081887138

M54	111	14.875	4105	9.18	10.05	497.8360244	2.236297199	2.275922637
M31	86	7.375	3949	5.11	9.95	710.3317233	1.293998481	1.318124873
S94	89.5	10.875	5242	11.68	10.40	829.4802108	2.228157192	2.260449325
S98	101	12.875	5085	11.01	9.65	607.4354325	2.16519174	2.211595759
M80	101.8725	9.77625	5160	12.27	11.90	840.6800525	2.377906977	2.380032005
S79	89.5925	8.6725	5087	8.13	11.83	724.9010898	1.598191468	1.600620982
S14	99.0275	9.845	5387	11.5	12.40	773.9370346	2.134768888	2.127171846
M52	81.475	7.8025	4038	5.19	10.37	711.7246144	1.285289747	1.304271557
S31	71.89	8.02875	4182	4.08	11.17	605.6767626	0.975609756	0.9828937
M59	73.245	7.9175	4050	5.87	11.77	692.8784174	1.449382716	1.452365252
S72	89.4825	8.495	3869	5.79	11.17	692.3864899	1.496510726	1.50768374
I23	125.25	26.70625	4229	19.48	11.40	550.5799685	4.606289903	4.631099364
M39	120.105	12.27375	4046	13.86	10.10	823.8830469	3.425605536	3.484721345
M16	112.64	13.5075	4008	10.23	10.30	606.7461276	2.55239521	2.59173403
S58	105.6825	9.6025	5095	11.43	10.80	773.9891259	2.243375859	2.267672348
I65	112.3025	17.5575	4193	13.84	10.50	631.600373	3.300739327	3.345545744
I74	123.81	19.5975	4143	16.82	10.40	632.7624484	4.059860005	4.118698556
M37	112.6425	10.5225	4061	10.49	9.80	765.1787233	2.583107609	2.634863863
S89	97.31	9.63125	5014	10.48	9.50	787.8618557	2.090147587	2.137867851
S100	83.9625	10.89	5020	9.63	10.00	767.3453251	1.918326693	1.95320536
I98	116.2425	20.09	4076	13.87	9.60	560.7275514	3.402845927	3.477360802
M98	111.965	9.70375	4005	10.73	8.80	859.4025394	2.679151061	2.757949622
I92	127.525	15.9025	4145	18.97	9.60	820.683636	4.576598311	4.676815792
I100	111.945	19.35875	4125	14.11	10.20	607.4763607	3.420606061	3.476478029
I97	118.9175	19.26625	4091	14.94	9.90	605.4681509	3.651918846	3.721700735
I81	126.5825	16.30125	4172	15.74	9.53	668.0176966	3.772770853	3.857850229
I71	124.76	20.42875	4147	16.62	10.23	598.5368683	4.007716422	4.072069665
I86	112.1025	15.99875	4138	13.75	10.07	687.9168587	3.322861286	3.381217477

I94	131.505	18.82375	4101	18.05	10.07	660.5105547	4.401365521	4.478540368
I75	118.77	17.92	4002	13.11	11.33	576.9814182	3.275862069	3.295576679
M90	117.7475	13.1275	4160	11.81	9.90	657.9758467	2.838942308	2.893189613
S29	88.09	9.10125	5373	7.58	16.00	624.6492274	1.410757491	1.362110681
S67	88.21	11.16625	5144	8.66	15.20	622.9056916	1.683514774	1.636750475
66	85.885	9.0775	4009	6.28	12.00	715.1610077	1.56647543	1.56647543
56	107.2475	10.065	4008	9.98	13.90	810.3098339	2.49001996	2.448483192
J	81.94	7.735	4008	6.54	12.57	904.9126832	1.631736527	1.623474203
59	105.2925	14.97625	4007	11.56	16.77	678.921623	2.884951335	2.76710242
79	100.635	16.115	4009	11.84	18.43	690.2016214	2.953354951	2.793006456
64	106.7175	8.74	4007	9.65	10.10	895.2004912	2.4082855	2.449845377
18	105.71	17.65375	4014	14.31	11.13	729.987182	3.565022422	3.592931802
66A	111.855	15.7825	3999	14.99	10.17	786.9107277	3.748437109	3.810701246
52	116.7925	17.84	4008	14.5	10.63	652.3321688	3.617764471	3.662565495
58	106.7875	16.105	4009	12.78	11.03	694.8014421	3.187827388	3.215677452
39	123.705	16.43	4012	15.54	10.10	699.5264346	3.87337986	3.940222928
61	110.4325	14.29875	4010	12.64	11.37	729.9260646	3.152119701	3.169950673

Table B2: Summary of mechanical properties for all specimens

Sample ID	Maximum Bending Moment (M_{max})	Modulus of elasticity in bending (E_s)	Modulus of elasticity from dynamic test (E_d)	Bending strength ($f_{m,0}$)	Second moment of area (I_B)	Flexural stiffness in bending ($EI_{m,s}$)	Flexural stiffness from dynamic test (EI_d)
	(kNm)	(N/mm^2)	(N/mm^2)	(N/mm^2)	(mm^4)	(Nmm^2)	(Nmm^2)
I73	4.69055	20269.9466	17462.75189	85.47821272	2387028.443	48384939066	41684085446
S37	2.388	13445.39601	18243.96687	40.38239171	2919775.056	39257531877	53268279379
M43	3.4561	17114.28693	24613.30811	80.97084496	1963430.171	33602707316	48326511755
M13	4.11985	23702.21969	23308.91217	85.46849494	2361953.959	55983551641	55054577392
I8	3.3844	22659.00771	19873.5523	85.12543174	1649948.754	37386201529	32790342850
M93	4.0207	20578.85694	18516.73963	79.21226521	2423720.929	49877406256	44879409366
M25	4.393	18747.34674	20229.68619	92.73666169	2250107.953	42183553995	45518977770
M30	2.6184	19221.40746	19558.80891	60.9187106	1896574.942	36454839729	37094746873
M72	5.2765	15884.50015	17804.7601	89.495444	2947915.427	46826163037	52486926973
M18	4.00545	18103.20037	18272.87824	76.5799505	2530213.75	45804966499	46234287772
M5	4.5761	17636.85494	18499.44038	92.7838757	2441339.6	43057552393	45163416375
M70	4.924	19504.46242	20457.9145	96.98221794	2475144.466	48276362203	50636293844
M78	6.79995	23290.44057	22051.36182	93.69787531	4018738.205	93598183326	88618650218
M64	7.169675	21420.1458	23050.82346	103.3004429	3739250.575	80095292476	86192804881
M82	4.1938775	14254.46237	14147.67971	54.72870552	4051827.477	57756622318	57323957399
I18	5.4765875	14464.70828	14594.92915	63.77260628	4433389.917	64127691847	64705011740
I38	5.948375	14113.77548	12696.72286	63.62433864	4943396.424	69769987234	62764934360
M85	6.294525	16979.31272	18411.30403	89.49253048	3692627.315	62698273935	67986084173
I2	6.7436	16051.16371	15575.3487	72.04068349	4972936.578	79821419116	77455221243
I15	5.1835675	13850.67682	14010.16904	50.48630868	5582830.082	77325975201	78216393178
I10	6.778675	14867.22381	14768.41636	63.90493542	5820830.398	86539588276	85964446877

S32	5.588885	17241.56555	15987.80893	90.11075684	3008086.182	51864115082	48092707121
M68	3.7797625	18928.00049	20232.01663	73.60740791	2484070.777	47018492871	50257761259
I44	6.227825	16049.92791	13640.83193	71.15461075	4463787.682	71643470510	60889777524
I93	5.1081275	16192.58982	16002.1022	61.86202696	4458937.066	72201738956	71352366649
I35	6.1065	13075.97387	14419.52914	62.90373073	5217884.078	68228915875	75239431484
I25	5.159015	14348.36324	13166.29872	48.89426463	5750496.906	82510218413	75712760027
M11	5.827625	17498.7497	18603.83245	82.24325705	3720065.614	65096497056	69207477382
I27	4.8659375	14140.92162	15703.21077	53.90798066	4783979.744	67649882569	75123842247
M100	4.3623525	14754.99928	14623.73074	55.93481969	4201707.313	61996188364	61444636407
I11	7.084	20099.73119	16979.51442	69.48754513	5658021.15	1.13725E+11	96070451710
I42	5.134405	16597.80726	16523.82496	63.73005736	4189374.23	69534426025	69224486482
M27	3.6025475	17535.23807	17566.45374	60.81076465	2947286.375	51681368251	51773369757
M10	4.45533	15989.09408	16440.73249	63.36285501	3594830.855	57478088747	59101652420
I4	7.840125	19794.69943	17597.0198	93.75262195	4348534.383	86077931071	76521245625
I7	7.549175	14295.82242	14588.34403	65.8222298	6436996.257	92022155416	93905115934
I21	7.1277	19058.73948	17493.86345	90.7714603	4024333.461	76698723000	70401140027
M34	5.3116775	19759.2337	19135.25619	105.8639673	2295485.912	45357042586	43924711004
M14	7.866575	19993.26315	18929.32576	86.76469567	5054608.362	1.01058E+11	95680328293
M49	4.0991175	24972.649	16768.69543	94.6996782	1937023.563	48372609560	32481358176
I52	4.2833475	16707.90755	17741.87244	71.09442504	2839220.527	47437434076	50373088411
I60	7.269725	20200.10644	18603.39063	95.17981173	3971700.439	80228771604	73887094733
I46	4.836095	17526.61466	15413.13765	72.95812353	3264580.655	57217047171	50317431002
I13	5.797725	16765.39605	16800.24918	66.68206548	4553785.86	76346023455	76504737143
M8	2.521605	15395.09699	17912.40573	73.07674624	1440636.237	22178734605	25805260799
I77	6.559025	13813.80249	13904.23799	64.73263075	5509539.474	76107690079	76605948038
M47	5.73804	18550.50828	18991.74744	67.60318272	4816840.818	89354845465	91480224302
M36	7.27145	17980.81231	19465.19832	90.88291989	4320485.087	77685831427	84099099037
I43	5.6450625	18103.96776	16042.18791	91.74200067	2861234.814	51799702841	45900466555

I6	9.41275	16784.08114	17547.94743	91.07454551	5787720.345	97141567892	1.01563E+11
M63	8.3559	15994.8794	17797.96206	83.44243062	5808102.621	92899900952	1.03372E+11
M79	4.92384	14133.85288	15127.31726	56.99735936	4718898.612	66696218737	71384276435
I69	8.033325	14754.26273	13977.88334	68.98419981	6623188.507	97720263378	92578156262
S65	2.568985	14332.07794	12101.33029	52.85719293	2053450.254	29430209093	24849479756
M38	4.86243	17680.3882	17197.2316	77.59514702	3141037.979	55534770818	54017157594
I54	9.044175	17596.67981	16262.56668	82.176903	6176970.698	1.08694E+11	1.00453E+11
S16	5.2870675	22972.03996	20489.07803	102.26854	2442725.196	56114380817	50049187148
I1	5.46434	15754.33816	16569.42185	67.31429495	4170443.554	65702578014	69101838540
M33	3.09189	15203.27105	17332.05115	69.56144591	2044623.112	31084959370	35437512354
M41	4.453605	15485.40693	18682.08596	59.42622705	4084416.672	63248854221	76305423348
I39	5.11865	15429.48838	15323.67687	59.7463713	4412158.751	68077352189	67610495024
M55	5.1168675	18494.90326	17227.79155	74.03448343	3568043.869	65990626171	61469516025
S34	2.630395	14806.90323	14011.43719	83.27952	1180494.474	17479467435	16540424170
M28	5.276545	16421.37975	17423.06233	69.73512614	4048105.641	66475479988	70530396917
M48	3.9482375	18847.65023	18344.22125	66.25585248	2942294.443	55455336529	53974100245
S62	2.847975	15698.17394	17487.68345	84.53172298	1398184.709	21948946762	24451011597
S92	3.92012	10945.38297	14826.14003	55.71361191	3535689.453	38699475136	52420626923
S63	6.422175	20239.61638	18358.81612	102.3622511	3082086.839	62380255282	56583465554
S55	3.879755	23697.01418	22131.27036	106.8397964	1602344.774	37970786822	35461925407
S78	4.6483575	19665.15985	20838.3056	94.29202166	2372440.433	46654420350	49437638752
S70	2.44789	17056.79085	16649.18735	72.86855086	1322733.437	22561587588	22022436817
S56	4.169325	20481.73807	21643.34305	77.76373717	2653956.651	54357644989	57440494243
S46	3.23403	21217.14933	20076.95585	148.0929386	772513.6145	16390536715	15509721733
I12	6.37675	14264.0111	15186.07943	70.00344303	4793713.77	68377586435	72797718081
M57	4.6536475	18680.93231	18018.23631	89.90456553	2406936.817	44963823747	43368756339
S47*	-	-	22400.3383	-	1186255.842	-	26572532162
S38*	-	-	19819.996	-	1595979.247	-	31632302296

S5*	-	-	-	-	876839.0427	-	-
S21*	-	-	23201.94807	-	1486054.876	-	34479368069
S54*	-	-	22760.01907	-	1788611.352	-	40708828474
S26*	-	-	18355.91886	-	1985904.267	-	36453097584
S97*	-	-	-	-	-	-	-
4S*	-	-	21608.93608	-	2909689.865	-	62875302307
S11*	-	-	24090.91886	-	2973118.54	-	71625157495
S23*	-	-	20442.68528	-	3143843.84	-	64268610190
4M*	-	-	21495.17904	-	3250899.496	-	69878666695
S50*	-	-	17749.00799	-	968509.9545	-	17190090923
S36*	-	-	21949.04406	-	2361786.797	-	51838962459
S51*	-	-	19377.54726	-	2807984.909	-	54411860295
S88*	-	-	20686.56121	-	3476265.137	-	71911971543
S13*	-	-	14953.79987	-	1417070.62	-	21190590454
S59*	-	-	18833.27486	-	879566.9611	-	16565126337
S1*	-	-	22007.7614	-	1062335.217	-	23379619982
S45*	-	-	18631.96666	-	2351563.31	-	43814249181
S87*	-	-	17784.32287	-	1405767.039	-	25000614897
M58*	-	-	23019.02423	-	5197865.88	-	1.1965E+11
S85*	-	-	-	-	1825870.863	-	-
S10*	-	-	22247.24893	-	1228397.72	-	27328469866
I83*	-	-	17822.28468	-	7624493.491	-	1.35886E+11
M96*	-	-	18932.182	-	6216716.532	-	1.17696E+11
I14*	-	-	-	-	7689120.695	-	-
M56*	-	-	20332.35036	-	2907012.918	-	59106405157
M91*	-	-	21099.23283	-	5679637.366	-	1.19836E+11
I82*	-	-	-	-	-	-	-
S93*	-	-	22653.18744	-	1035313.587	-	23453152736

S82*	-	-	-	-	-	-	-
M40*	-	-	18622.69071	-	5536561.247	-	1.03106E+11
M65*	-	-	22646.6537	-	4297467.245	-	97323252477
S64*	-	-	19952.99135	-	2127367.039	-	42447336114
S44*	-	-	18860.88231	-	1443266.685	-	27221283097
S8*	-	-	-	-	-	-	-
M87*	-	-	18621.45816	-	2277884.125	-	42417523943
M62*	-	-	20684.89317	-	2424683.955	-	50154328583
M29*	-	-	-	-	-	-	-
M53	2.41983	28200.39864	22997.22325	68.96848513	1559310.67	43973182503	35859815605
I24	9.808925	15295.83685	13628.88138	71.65655513	8051925.306	1.23161E+11	1.09739E+11
I49	4.9466675	13876.963	12072.33519	60.04594825	4074994.484	56548547695	49194699294
I55	6.197925	14122.97248	15295.44668	60.38803394	5704324.211	80562013872	87250186792
M45	5.343245	23058.50915	19712.78088	98.13134749	2640140.98	60877714943	52044520621
I22	7.6613	16399.88025	16452.46666	73.22606172	5917215.646	97041628031	97352793147
I50	5.588885	17136.19329	14849.72982	72.18322547	3856510.622	66085911424	57268140793
I9	8.850975	14630.81929	17008.29889	81.64799886	6088785.338	89083917994	1.0356E+11
M94	8.550825	16141.92814	18255.91898	80.43148456	6445558.404	1.04044E+11	1.1767E+11
I84	13.46765	13879.42645	15872.48208	74.82558692	12076693.05	1.67618E+11	1.91687E+11
I37	8.654325	16638.94732	17085.29939	84.3277174	5637445.253	93801154600	96317439912
M99	5.3046625	15800.57112	16984.04812	69.26050409	4302922.336	67988630395	73081040006
I87	6.522225	15718.2997	15627.76424	66.41778411	5216505.63	81994598895	81522320162
I45	10.91465	13748.25931	13915.20597	80.08685305	8212203.343	1.12904E+11	1.14275E+11
S90	7.6015	24423.45616	23756.14996	118.0166269	3319929.86	81084161380	78868751608
I76	8.236875	16941.35199	16464.19242	80.00033161	5681103.58	96245575432	93534782479
I36	13.4573	15825.26072	15191.4112	83.92147062	10105225.71	1.59918E+11	1.53513E+11
M76	6.64355	15929.34635	18836.33281	92.8454553	3811999.42	60722659049	71804089764
I70	5.9363	16251.26998	19388.04101	77.14682127	4178569.458	67907060371	81014276028

I34	4.7449	16117.28714	16153.65586	70.43251652	3371180.512	54334284316	54456889836
I67	10.091825	17863.58125	17411.8224	97.93903693	5658675.05	1.01084E+11	98527844989
M83	10.5409	17331.75544	19860.11113	106.4496214	5775730.684	1.00104E+11	1.14707E+11
M66	8.957925	16985.04586	19334.81255	81.77487209	6554412.514	1.11327E+11	1.26728E+11
S40	5.987475	17115.91358	21150.6526	107.0906647	2709344.973	46372914424	57304414300
S99	3.1901575	16024.50123	14159.82618	75.10856427	1883454.277	30181415383	26669385182
M6	6.268075	18241.98043	20197.66383	92.59233098	3555531.713	64859939920	71813434268
I57	9.12295	14138.58816	17439.78349	68.76944439	8308989.184	1.17477E+11	1.44907E+11
M92	7.50145	17377.44248	21077.95712	98.79291459	4115368.14	71514573134	86743553187
I20	7.9511	10959.64005	14782.27216	56.56306804	8572693.284	93953632645	1.26724E+11
I19	4.5922375	11438.8938	12287.66148	44.53234243	5739092.62	65648870973	70520027333
I80	10.635775	14472.25073	17276.23556	64.93677249	10802547.05	1.56337E+11	1.86627E+11
I88	12.081325	16797.54117	17765.58846	71.38457561	11184198.46	1.87867E+11	1.98694E+11
I35	16.538725	17806.43562	17408.28571	117.4518817	8689556.141	1.5473E+11	1.5127E+11
M84	8.273675	16811.56461	19175.01066	75.59604218	6782224.08	1.1402E+11	1.30049E+11
I66	13.64705	16637.55994	15893.99848	97.71858937	8366131.107	1.39192E+11	1.32971E+11
I79	8.9263	15294.30997	17060.04374	76.86799732	6760655.231	1.034E+11	1.15337E+11
I3	8.4088	12240.40233	16803.73789	65.58481087	7678172.619	93983921977	1.29022E+11
I32	11.29185	14933.67785	15823.57345	88.31672706	7645487.133	1.14175E+11	1.20979E+11
I56	10.235575	16501.87437	16750.40469	87.50701451	6773360.543	1.11773E+11	1.13457E+11
I16	10.128625	13581.68794	15177.96484	73.81338546	8195768.91	1.11312E+11	1.24395E+11
I17	9.287975	14000.05727	16189.18161	78.74568861	6850772.626	95911209073	1.10908E+11
I64	10.391975	16896.32147	17247.40933	76.79973514	8197578.081	1.38509E+11	1.41387E+11
I89	10.81115	15493.38349	18806.24392	86.58442313	7598353.093	1.17724E+11	1.42896E+11
S33	1.60563	18069.96849	20483.7781	50.01852762	1293176.901	23367665854	26489148690
S96	4.16231	19168.28642	23447.93305	73.281036	2910182.052	55783203115	68237753910
S75	2.800595	18443.44455	23361.4645	71.91248536	1755958.332	32385920121	41021758224
S68	2.298735	19191.18922	16133.03358	74.28052507	1183091.247	22704927989	19086850819

S86	3.1778525	22861.18846	20287.65214	90.96515448	1442371.926	32974336435	29262339891
S9	3.0006375	17359.75022	19600.28812	73.28897973	1822966.907	31646250153	35730676612
S25	2.1513625	12637.72451	18373.92958	82.63323104	977259.1441	12350331841	17956090694
S95	5.3116775	23279.37629	24890.38337	101.1270723	2510421.99	58441058152	62485365750
S91	3.1147175	21229.22757	15996.80241	77.37724514	1719636.456	36506553660	27508684594
S12	2.781275	17295.15453	17479.26877	84.29903141	1340586.654	23185653333	23432474435
S28	3.628825	21385.71316	19470.33873	96.35915982	1575809.154	33699802549	30681538004
S24	3.918395	25685.48533	22067.87829	120.7784379	1294834.121	33258442823	28574241792
S49	1.56699	19605.77152	19700.2829	64.32123159	922343.0574	18083247251	18170419165
S17	-	-	20398.38538	-	1738012.536	-	35452649501
S35	4.1798475	13836.55925	16475.4947	81.30845093	2490169.356	34455375849	41026772033
S20	3.5095125	16394.10448	16887.29559	64.71018476	2563588.245	42027733542	43292072476
S69	3.8815375	13478.24754	16476.68705	75.99960568	2467470.44	33257177394	40655738250
S76	3.3902	20123.37431	19764.04488	88.43575521	1683872.486	33885196325	33280131394
S57	2.284705	24216.83284	22041.93933	96.46211622	894493.544	21661800635	19716372428
S7	2.639135	20759.8229	18942.79187	74.05792711	1474086.888	30601782725	27923321107
S27	2.5584625	22288.14	19440.9021	85.62255087	1189551.013	26512879513	23125944786
S60	2.11623	14725.3671	14356.87889	57.00928809	1470586.628	21654927946	21113034111
S83	6.191025	22825.3153	21361.23275	136.9561473	1995323.678	45543892075	42622573497
S39	6.3365	17610.32852	20207.81928	90.39392747	3758256.073	66184124087	75946159539
S3	2.507575	18576.0491	17059.41489	70.37187739	1433790.781	26634167947	24459631805
S48	3.16733	16398.2998	15155.3192	94.58872472	1300693.873	21329168075	19712430827
S74	4.874735	17996.51031	23570.85289	84.78139296	3014676.223	54253651711	71058489758
S42	1.7319575	11286.71262	16150.3885	53.63799657	1367430.55	15433795648	22084534636
S15	3.4060125	16634.54391	15433.24844	83.31707807	1705978.683	28378177325	26328792851
S53	1.810905	13692.93073	13808.19242	48.97290336	1535082.715	21019781282	21196717500
S6	4.083305	15300.51892	15698.28285	68.38643187	2953743.728	45193811786	46368704519
45**	3.40423	26716.57144	-	134.2585016	960413.8306	25658964717	-

75**	1.3652225	12382.90155	-	49.34116418	1064393.269	13180277060	-
41**	3.6797125	15946.08854	-	71.72846151	2367458.17	37751697594	-
36**	6.634925	14621.90743	-	88.21983423	4061191.675	59382368740	-
31**	3.6797125	15946.08854	-	71.72846151	2367458.17	37751697594	-
78**	4.16231	26294.70641	-	68.60448277	2784803.868	73225600137	-
F**	2.2355425	22490.13563	-	103.5797055	793519.4835	17846360812	-
10**	2.833945	18723.30455	-	133.3112141	805523.0884	15082054102	-
54**	8.57555	-	-	118.6057761	3609454.697	1.28099E+11	-
73**	4.855415	14446.53034	-	80.77587716	2997671.515	43305952499	-
16**	4.71155	19877.70512	-	117.0495124	1811066.18	35999839488	-
53**	-	-	-	-	2801957.116	-	-
47**	4.46936	20120.75563	-	96.89603091	2106543.161	42385240153	-
71**	7.90855	23074.12616	-	127.8096051	3213225.762	74142376607	-
77**	3.6516525	20942.23307	-	102.7628312	1553224.341	32527986164	-
1**	4.53077	27668.74203	-	143.1434097	1199609.422	33191683638	-
E**	3.653435	18721.02368	-	99.1788088	1660605.242	31088230059	-
77A**	5.950675	14402.32708	-	81.38444773	3602253.875	51880838526	-
76**	1.90394	16834.84392	-	83.13182019	837722.1284	14102921279	-
H**	4.027185	-	-	165.8459004	904439.235	38734502652	-
31A**	-	-	-	-	2359993.115	-	-
67**	-	-	-	-	1451437.447	-	-
I**	4.2675925	18451.00525	-	78.72439211	2725845.81	50294595345	-
62**	2.21099	-	-	139.9857013	530968.2034	16074345224	-
12**	5.819	17118.84369	-	108.3135385	2735407.438	46827012362	-
4**	8.1788	13829.86165	-	104.7033452	3888906.865	53783043904	-
38**	3.66919	17102.97788	-	84.52431643	1976777.177	33808776324	-
43**	5.73804	28303.32234	-	164.9577716	1585713.261	44880953572	-
16A**	3.3059625	13389.36012	-	45.6121084	3519897.281	47129172280	-

74**	5.276545	-	-	106.7268511	2475446.483	79784378593	-
72**	6.364675	19095.2612	-	73.86275945	4458595.897	85138053211	-
73A**	-	-	-	-	2458568.233	-	-
6**	7.7211	23861.94929	-	80.01377243	5277790.314	1.25938E+11	-
75A**	5.4959075	19738.29206	-	96.77770634	2586170.276	51046584229	-
80**	2.8918475	16829.96434	-	65.77482337	1974562.293	33231812977	-
7**	4.107915	21254.4163	-	94.42739028	2039005.584	43337873517	-
89**	7.31055	15265.85826	-	72.89240194	5625773.786	85882265239	-
I85***	-	21592.80174	18457.09217	-	4804375.82	1.0374E+11	88674807341
M20***	-	20325.28326	19162.31875	-	2570718.988	52250591610	49260936671
M86***	-	15078.79115	16427.5327	-	4023089.682	60663329089	66089437315
I72***	-	17589.21117	15786.45117	-	4771928.407	83934456431	75331814773
I31***	-	10929.90398	12212.74101	-	4008109.835	43808255641	48950007347
M61***	-	15293.66256	18262.01786	-	3016270.979	46129830540	55083194482
M32***	-	17426.85337	19964.28586	-	4189844.42	73015804350	83647251721
M89***	-	22095.56151	20546.40563	-	4529666.208	1.00086E+11	93068359274
S91***	-	16648.46418	17191.10555	-	4583956.933	76315842780	78803287479
I51***	-	18910.15557	16623.52143	-	3865684.621	73100697564	64261291124
M60***	-	15731.0369	19777.34533	-	2650073.821	41688409066	52411425109
S18***	-	16854.56324	18161.30481	-	1528145.911	25756231908	27753123683
M81***	-	17586.12044	19670.93073	-	4847042.777	85240678075	95345842742
M9***	-	16879.53756	17542.76382	-	4308932.076	72732780830	75590577727
M22***	-	20976.06176	21845.4781	-	3657952.372	76729434885	79909718426
M73***	-	22961.51042	22939.63002	-	1594331.565	36608260846	36573376234
M54***	-	18053.96759	15018.44158	-	5312551.653	95912635378	79786246649
M31***	-	19333.07957	21587.69704	-	1420065.126	27454232067	30655935713
S94***	-	18644.33078	19968.79047	-	2115442.038	39441001091	42242818807
S98***	-	17244.19352	16469.55819	-	3534084.927	60942444412	58204817365

M80***	-	26710.43095	21322.09045	-	3032665.038	81003790071	64662758228
S79***	-	20213.81389	20839.31549	-	1825289.62	36896064671	38037786261
S14***	-	22384.45517	20958.19289	-	2775715.765	62132885102	58173986400
M52***	-	20575.56875	19252.02163	-	1238950.701	25492115338	23852305705
S31***	-	21279.37811	17572.78902	-	834124.399	17749648481	14657892079
M59***	-	20973.79939	22148.17348	-	1925004.597	40374660249	42635335773
S72***	-	18200.12099	21611.27706	-	1791552.217	32606467113	38717731330
I23***	-	15019.72079	13295.60282	-	10835802.39	1.62751E+11	1.44069E+11
M39***	-	17688.51339	20074.14166	-	6121552.612	1.08281E+11	1.22885E+11
M16***	-	15464.93985	17921.80791	-	5263470.63	81399256682	94330909538
S58***	-	20609.52461	21481.48563	-	3377999.936	69618972793	72564457086
I65***	-	14946.87216	17853.79771	-	6065340.645	90657871207	1.08289E+11
I74***	-	16945.88627	16970.34184	-	9018059.037	1.52819E+11	1.5304E+11
M37***	-	18778.75649	21260.73378	-	4447316.007	83515064330	94553201646
S89***	-	20311.14218	19648.86237	-	2580088.388	52404542092	50695801657
S100***	-	17280.80956	17305.35683	-	1705649.427	-	-
I98***	-	15189.66663	14789.76715	-	7319454.57	1.1118E+11	1.08253E+11
M98***	-	14968.17029	23224.75057	-	4111741.999	61545254424	95494182322
I92***	-	14277.9397	20986.71694	-	8861495.982	1.26524E+11	1.85974E+11
I100***	-	14695.23624	14392.66785	-	6297380.136	92541488795	90636100598
I97***	-	14035.20101	15082.38156	-	7766812.571	1.09009E+11	1.17142E+11
I81***	-	12634.05014	16465.33192	-	8773496.463	1.10845E+11	1.44459E+11
I71***	-	12708.31812	15827.1365	-	9459857.5	1.20219E+11	1.49722E+11
I86***	-	15399.49079	16680.56851	-	5731113.425	88256228418	95598230117
I94***	-	13972.96158	14896.23171	-	10871130.53	1.51902E+11	1.61939E+11
I75***	-	16502.43496	16297.16811	-	7446047.819	1.22878E+11	1.21349E+11
M90***	-	15372.98884	18889.84259	-	5996124.314	92178352197	1.13266E+11
S29***	-	17056.75641	19654.90213	-	1784779.079	30442541999	35079658129

S67***	-	14385.13032	17014.20397	-	2047423.553	29452454636	34835281940
66***	-	18603.61913	-	-	1637801.097	30469027807	-
56***	-	16572.405	-	-	3666666.817	60765487497	-
J***	-	21846.13727	-	-	1254622.685	27408659400	-
59***	-	14305.26503	-	-	4451854.15	63684953475	-
79***	-	13117.90765	-	-	3959828.876	51944669481	-
64***	-	18476.674	-	-	3253812.694	60119636414	-
18***	-	12214.20852	-	-	4923698.664	60139082185	-
66A***	-	16836.71777	-	-	5644141.26	95028813450	-
52***	-	11418.52352	-	-	7008527.326	80027034100	-
58***	-	19953.53153	-	-	4864940.501	97072743683	-
39***	-	13374.59812	-	-	8151973.292	1.09029E+11	-
61***	-	20247.76985	-	-	5099044.222	1.03244E+11	-

* Results discarded due to errors in data collection – refer to Section 6.1

** MTG Timber Grader unavailable for testing

*** Specimens which failed in shear

Table B3: Equation of slope for each specimen for deflection at mid-span (δ, mm) induced by the application of a lump mass (F_{app}, kN) and the calculated bending stiffness (EI, Nmm^2)

Sample ID	Gradient of slope (δ = gradient x F_{app})	Calculated EI (Nmm^2)
10	0.0405	1.84861E+10
66	0.023	3.25516E+10
36	0.0106	7.06309E+10
41	0.0196	3.81983E+10
16A	0.0262	2.85759E+10
56	0.0121	6.18750E+10
59	0.0089	8.41222E+10
77	0.0209	3.58224E+10
31	0.025	2.99475E+10
12	0.0118	6.34481E+10
4	0.0128	5.84912E+10
73	0.015	4.99125E+10
75	0.0445	1.68244E+10
7	0.0174	4.30280E+10
61	0.007	1.06955E+11